

Radiative rates for E1, E2, M1, and M2 transitions in S-like to F-like tungsten ions (W LIX to W LXVI)

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Abstract

Calculations of energy levels, radiative rates and lifetimes are reported for eight ions of tungsten, i.e. S-like (W LIX) to F-like (W LXVI). A large number of levels has been considered for each ion and extensive configuration interaction has been included among a range of configurations. For the calculations, the general-purpose relativistic atomic structure package (GRASP) has been adopted, and radiative rates (as well as oscillator strengths and line strengths) are listed for all E1, E2, M1, and M2 transitions of the ions. Comparisons have been made with earlier available experimental and theoretical energies, although these are limited to only a few levels for most ions. Therefore for additional accuracy assessments, particularly for energy levels, analogous calculations have been performed with the flexible atomic code (FAC).

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1. Introduction

Tungsten (W) is one of the most important constituents of tokamak reactor walls [1]. Additionally, it radiates strongly over almost all ionisation stages. For example, the most intense emission lines of W ions [1] are from W XXII to W L in the VUV to the soft x-ray region, covering an electron temperature range from about 0.5 to 5.0 keV. Similarly, Pütterich et al. [1] have predicted emission features from W LXI to W LXIX in the 0.1–0.15 nm, 1.8–4.0 nm and around 8 nm ranges. However, to assess radiation loss and for modelling plasmas, atomic data (including energy levels and oscillator strengths or radiative decay rates) are required for many of the W ions. Their need for atomic data for several ions, including those of W, has increased significantly due to the developing ITER project. Therefore, several groups of people are actively engaged in producing atomic data.

Early calculations for a number of W ions (W XXXVIII to W XLVIII) were performed by Fournier [2]. He adopted a relativistic atomic structure code, but reported only limited results for energy levels and oscillator strengths (f -values). A thorough critical compilation of experimental, theoretical and analytical energy levels of W ions (W III through W LXXIV) has been undertaken by Kramida and Shirai [3] and has been further reviewed by Kramida [4]. These energy levels, along with some spectral lines, are also available on the NIST (National Institute of Standards and Technology) website at <http://www.nist.gov/pml/data/asd.cfm>. Recently, spectra in the EUV wavelength range (4–20 nm) have been measured by Ralchenko et al. [5], for a number of W ions, namely W LV to W LXIV. Similarly, Clementson et al. [6] have discussed spectroscopy of many W ions (W XLVII to W LXXII). On the other side, calculations have been performed for several W ions, such as by Quinet [7] for W XLVIII to W LXII. Although he adopted the GRASP code for the calculations, his reported results for energy levels and radiative rates (A -values) are confined to

forbidden lines within the $3p^k$ and $3d^k$ configurations. However, for the modelling of plasmas, atomic data among a wider range of levels/transitions are preferred. Therefore, we have already reported such data for two W ions, namely W XL [8, 9] and W LVIII [10, 11]. In this paper, we extend our work to eight other W ions, S-like (W LIX) to F-like (W LXVI).

As in our earlier research [8–11] and those of others [7, 12], we have adopted the fully relativistic multi-configuration Dirac-Fock (MCDHF) atomic structure code [13], better known as the general-purpose relativistic atomic structure package (GRASP) [14]. This code is based on the jj coupling scheme, includes higher-order relativistic corrections arising from the Breit interaction and QED (quantum electrodynamics) effects, and is suitable for the heavy ions considered here. However, this original version [13] has undergone several revisions, such as by [14–16], and the one employed here (and by many other workers) has been revised by Dr. P. H. Norrington, and is freely available at <http://web.am.qub.ac.uk/DARC/>.

2. Energy levels

Extensive configuration interaction (CI) has been incorporated in GRASP, as described below for each ion, and for the optimisation of the orbitals the option of ‘extended average level’ (EAL), in which a weighted (proportional to $2j+1$) trace of the Hamiltonian matrix is minimised, has been adopted. The GRASP code has a few other choices for optimisation, such as average level (AL) and extended optimal level (EOL). However, in general, the results obtained with the AL option are comparable with those of EAL as already discussed and demonstrated by us for several other ions, such as those of Kr [17] and Xe [18]. Similarly, the EOL option may provide slightly more accurate data for a few predefined levels, but is only useful if the experimental energies are known, which is not the case for a majority of the levels of the ions studied here.

2.1. S-like W LIX

Clementson and Beiersdorfer [19] have measured wavelengths for 3 lines of W LIX. They also calculated these with two different codes, i.e. GRASP and FAC (flexible atomic code), and there is no (major) discrepancy among the results. For modelling purposes, Feldman et al. [20] calculated atomic data for many W ions, including W LIX, but did not report the data. Furthermore, they used a simple model consisting of the $3s^23p^4$, $3s3p^5$, $3s^23p^33d$, and $3p^6$ configurations, generating 48 levels in total.

For our work, we have performed two sets of calculations using the GRASP code. In the first (GRASP1) we have included 2762 levels of the all possible combinations of the $n = 3$ orbitals, i.e. 18 configurations in number. The second (GRASP2) involves an additional 28 configurations, which are $[3s^23p^3, 3s^23p^23d, 3s3p^4, 3s3p^33d, 3s^23p3d^2, 3s3p^23d^2, \text{ and } 3p^5]4\ell$. These 46 configurations generate 12 652 levels in total. In Table A we compare the energies obtained from both models, but for only the lowest 20 levels. Differences between the two sets of energies are less than 0.025 Ryd and the inclusion of larger CI in the GRASP2 calculations has lowered the energies for most of the levels. Therefore, it is necessary to assess the effect of further CI on the energy levels. For this we have adopted the FAC code of Gu [21], which is also fully relativistic and is available from the website <https://www-amdis.iaea.org/FAC/>. This code is comparatively more efficient to run and generally yields results similar to those obtained with other atomic structure codes, as has already been demonstrated in several of our earlier papers – see for example Aggarwal et al. [22]. With FAC we have also performed two sets of calculations, i.e. FAC1: includes the same 2762 levels as in GRASP1, and FAC2: also includes levels of the $3\ell^54\ell$ configurations, generating 38 694 levels in total. Energies obtained from both these models are also listed in Table A for comparison.

Discrepancies between the GRASP1 and FAC1 energies are up to 0.15 Ryd (see level 13), in spite of including the *same* CI. This is because of the differences in the algorithms of the codes and also in calculating the central potentials. Additionally, the energies

obtained from FAC are generally lower for most levels. However, inclusion of additional CI in the FAC2 calculations further lowers the energies, but only up to 0.02 Ryd for some of the levels. Therefore, it may be reasonable to say that the inclusion of CI in our GRASP2 calculations is sufficient to calculate accurate results, but differences with FAC2 remain of up to 0.15 Ryd. The NIST compilation is only for a few levels of W LIX, which are mostly based on the experimental and theoretical work of Clementson et al. [6]. However, these energies are not very accurate as indicated on their website, and many levels are also missing from the compilation. Nevertheless, in Table A we have included their energies for comparison. Unfortunately, differences between their compiled energies and our (any of the) calculations are up to 0.4 Ryd for some of the levels, such as 18–20. Therefore, there may be scope to improve upon our calculated energies but the (in)accuracy cannot definitely be determined by the limited comparison shown in Table A.

Our calculated energies from GRASP2 are listed in Table 1 along with those from FAC2 for the lowest 220 levels, which belong to the $n \leq 3$ configurations. Beyond these, the levels of the $n = 4$ configurations start mixing. Discrepancies between the two sets of energies are smaller than 0.4 Ryd ($< 0.5\%$) for a majority of levels and the orderings are different only in a few instances, such as 70/71 and 151/152. We also note that some differences may be because of a mismatch between the two sets of energies, as it is not always possible to perfectly match these due to their different notations. Also note that the *LSJ* designations of the levels listed in Table 1 are not always unambiguous, and a few of these can be (inter)changed with varying amounts of CI, codes, and authors preferences. This is inevitable in any calculation because of the strong mixing among some of the levels. As examples, we list the lowest 20 levels in Table B. For some, such as 1, 2, 10, and 12, there is a clear dominance of one vector (level) and hence there is no scope for ambiguity. However, for others, such as 3–9, several vectors (levels) dominate and therefore it is not straightforward to designate such levels. For example, the eigenvector for level 19 is dominant in 19 but is also significant in 4. However, the eigenvector for level 105 is dominant in both levels 4 and 105 (not listed in Table B). Finally, it may be noted that the degeneracy among the levels of W LIX is very large – see for example levels 3, 5, 9, 19, and 32 of $3s^2 3p^3 3d^5 D^o$, which are separated by up to ~ 30 Ryd. For the ground state energy the Breit and QED contributions are 28.7 and 21.7 Ryd, respectively, although they amount to only $\sim 0.1\%$.

2.2. *P-like W LX*

For this ion we have also performed two calculations with GRASP using different levels of CI, i.e. GRASP1: includes 1313 levels of the 15 $n = 3$ configurations, which are $3s^2 3p^3$, $3s^2 3p^2 3d$, $3s 3p^4$, $3s^2 3p 3d^2$, $3s 3p^3 3d$, $3s 3p^2 3d^2$, $3p^5$, $3p^4 3d$, $3s^2 3d^3$, $3p^3 3d^2$, $3s 3p 3d^3$, $3p^2 3d^3$, $3s 3d^4$, $3p 3d^4$, and $3d^5$. In the other calculation (GRASP2), a further 20 configurations of $[3s^2 3p^2, 3s 3p^3, 3s^2 3p 3d, 3s 3p^2 3d, \text{ and } 3s^2 3d^2] 4\ell$ are included, generating in total 3533 levels. Similarly, two calculations with FAC are performed, i.e. FAC1 with the same CI as in GRASP2, and FAC2, which also includes all possible combinations of $3\ell^4 4\ell$, generating 14 608 levels in total. Energies for the lowest 220 levels from both GRASP2 and FAC2 are listed in Table 2. These levels belong to the first 8 configurations listed above. For the higher-lying levels, those of $n = 4$ intermix with $n = 3$.

In Table C we compare our energies for the lowest 25 levels of W LX from GRASP1, GRASP2, FAC1, and FAC2 with the NIST compilation. CI for W LX is not as important as for W LIX, because differences between our GRASP1 and GRASP2 energies are smaller than 0.02 Ryd. Similarly, discrepancies between the FAC1 and FAC2 energies are less than 0.03 Ryd. However, differences between the GRASP2 and FAC2 energies are up to 0.3 Ryd for some levels, for reasons already explained in section 2.1. The NIST compilation is only for the lowest 25 levels, listed in Table C, and our GRASP2 energies are (generally) lower by up to 0.3 Ryd – see for example, levels 13, 17 and 22. Similar differences remain between the NIST and FAC2 energies, and therefore are not due to

a lack of CI. However, it is worth emphasising that the compiled energies of NIST are mostly based on interpolation/extrapolation and hence are likely not very accurate. More importantly, there are differences in the designations of a few levels, particularly the ground state, which is $(3s^23p^3) \ ^2D_{3/2}^o$ in our work, but $^2P_{3/2}^o$ in NIST. This is a highly mixed level and the eigenvector for $^2P_{3/2}^o$ dominates in both levels 1 and 25 – see Table D in which eigenvectors for the lowest 25 are listed. However, we have preferred to designate the lower (ground) level as $^2D_{3/2}^o$, because the placings of $^2D_{5/2}^o$ and $^2P_{1/2}^o$ (levels 5 and 6) are unambiguous. There may be similar differences in designations with other calculations because of the very high mixing among some of the levels of W LX.

2.3. Si-like W LXI

As for other W ions, we have performed two calculations each with the GRASP and FAC codes to assess the effect of CI. These are GRASP1: 518 levels of 12 configurations $[3s^23p^2, 3s3p^3, 3s^23p3d, 3s3p^23d, 3p^4, 3s^23d^2, 3p^33d, 3s3p3d^2, 3p^23d^2, 3s3d^3, 3p3d^3, \text{ and } 3d^4]$; GRASP2: 4364 levels of 48 configurations, the additional 36 are $[3s^23p, 3s3p^2, 3s^23d, 3s3p3d, 3p^3, 3p^23d, 3s3d^2, 3p3d^2, \text{ and } 3d^3]4\ell$; FAC1: 9798 levels of $3^*4, 3^*3 \ 4^*1$ and $3^*4 \ 5^*1$; and finally FAC2: which includes 27 122 levels in total, the additional ones arising from $3^*3 \ 6^*1$ and $3^*2 \ 4^*2$ configurations. Energies obtained from these calculations are compared in Table E with the NIST compilation for the lowest 21 levels of W LXI, which are the only ones in common. As for other ions, the CI is not very important for this ion, because the GRASP1 and GRASP2 energies agree within to 0.02 Ryd, and the FAC1 and FAC2 energies show no appreciable differences. Similarly, the agreement between our GRASP2 and FAC2 energies is better than 0.2 Ryd – see levels 12–15. However, as for other ions, the differences with the NIST compilation are larger, up to 0.4 Ryd – see level 9 for example. Again, the NIST energies are not very accurate and therefore such differences are not surprising. An important difference between our calculations and the NIST compilation is the designation for level 4, i.e. $(3s3p^3) \ ^5S_2^o$ which is $^3P_2^o$ (64) in the latter. Both these levels are highly mixed, as may be seen from the eigenvectors listed in Table F for the lowest 21 levels *plus* the remaining two of the $3s3p^3$ configuration, i.e. $^3P_2^o$ and $^1P_1^o$.

Our recommended energies for the lowest 215 levels of W LXI are listed in Table 3 from the GRASP2 and FAC2 calculations. These levels belong to the $n = 3$ configurations and beyond these those of $n = 4$ intermix. Finally, there are no major differences in the orderings of the two sets of level energies.

2.4. Al-like W LXII

For W LXII the experimental energies are also as sparse as for other W ions. However, two sets of theoretical energy levels [12, 23] are available in the literature. Safronova and Safronova [23] adopted a relativistic many-body perturbation theory (RMBPT) and reported energies for the lowest 40 levels belonging to the $3s^23p, 3s3p^2, 3s^23d, 3s3p3d, 3p^3, \text{ and } 3p^23d$ configurations. In addition, S. Aggarwal et al. [12] have calculated energies for the lowest 148 levels of the $3s^23p, 3s3p^2, 3s^23d, 3s3p3d, 3p^3, 3p^23d, 3s3d^2, 3p3d^2, \text{ and } 3d^3$ (nine) configurations, adopting the same version of the GRASP code as in the present work. The RMBPT energies [23] are closer to the NIST compilation and in general are lower than those of S. Aggarwal et al. by up to 0.4 Ryd – see Table 2 of [12].

We have performed several sets of calculations with the GRASP code but mention only three here, namely: GRASP1, which includes the basic 148 levels of the 9 configurations listed above; GRASP2, which considers an additional 776 (total 924) levels of the $[3s3p, 3s3d, 3p3d, 3s^2, 3p^2, \text{ and } 3d^2]4\ell$ (24) configurations; and finally GRASP3 which includes a further 1079 levels (total 2003) of the 30 additional configurations, i.e. $[3s3p, 3s3d, 3p3d, 3s^2, 3p^2, \text{ and } 3d^2]5\ell$. S. Aggarwal et al. [12] included CI among 35 configurations, which are the basic 9 of GRASP1 *plus* another 26, i.e. $3s3p4\ell, 3s3d4\ell, 3p3d4\ell, 3s^24\ell, 3p^24\ell$ (except $3p^24d$),

$3p4\ell^2$ (except $3p4p^2$), and $3d4\ell^2$. It is not clear why they overlooked configurations such as: $3p^24d$, $3p4p^2$, $3s4\ell^2$, and $3\ell4\ell\ell'$. In addition, their 35 configurations generate 1007 levels in total (see Table 1 of [24]) whereas they mention only 894, and therefore there is an anomaly of 113 levels. However, we stress that (particularly) the omission of the $3p^24d$ and $3p4p^2$ configurations does not affect the energies or the corresponding lifetimes, as already discussed by one of us [24]. More importantly, levels of the $3\ell4\ell^2$ configurations lie at energies well above those of our GRASP3 calculations, and hence are omitted from our work. This has been confirmed by our larger calculation with 75 configurations and 2393 levels. For the same reason we preferred not to include the $4\ell^2$ configurations for the calculations of energy levels for other W ions. A complete set of energies for all 148 levels (of the GRASP1 calculations) are listed in Table 4 from GRASP3 and FAC2 (see below). We note that levels from all other configurations clearly lie *above* these 148 and hence there is no intermixing.

As with GRASP, we have also performed several calculations with FAC, but focus on only two, i.e. FAC1: includes the same 2003 levels as in GRASP3, and FAC2: contains 12 139 levels in total, the additional ones arising from the $3*2\ 6*1$, $3*1\ 4*2$, $3*1\ 5*2$ and $3*1\ 6*2$ configurations. In Table G we compare our energies from GRASP2, GRASP3, FAC1, and FAC2 with those of NIST for the lowest 21 levels, which are in common. Also included in this table are the results of Safronova and Safronova [23] from RMBPT. The corresponding data of S. Aggarwal et al. [12] are not considered because they are similar to our GRASP2 calculations and have already been discussed previously [24]. Although a considerably large CI has been included in our calculations, it does not appear to be too important for W LXII, because the GRASP2 and GRASP3 (and FAC1 and FAC2) energies are practically identical. Therefore, the discrepancies between the GRASP and FAC energies (up to 0.4 Ryd, particularly for level 21) are not due to different levels of CI but because of the computational and theoretical dissimilarities in the codes. Nevertheless, although the NIST energies are not claimed to be very accurate, their agreements with those from FAC and RMBPT are better (within 0.1 Ryd) than with GRASP. Regarding all the 148 levels in Table 4, the differences between the GRASP and FAC energies are up to 0.4 Ryd for some (see levels 77 upwards in the table).

Finally, as for other W ions, configuration mixing is strong for W LXII also and therefore there is always a possibility of (inter)change of level designations listed in Table 4. For the 21 levels listed in Table G, their designations and orderings are the same between NIST and our calculations, but differ with those of S. Aggarwal et al. [12] for some, such as levels 10 and 68, i.e. $(3p^3)\ ^2D_{3/2}^o$ and $^2P_{3/2}^o$, which are reversed by them. These two levels (and many more) have strong mixing, as may be seen from Table H in which we list the eigenvectors for the lowest 21 levels plus 68, i.e. $3p^3\ ^2P_{3/2}^o$. Similarly, there is a *disagreement* for most level designations between our work and NIST with those of Safronova and Safronova [23].

2.5. Mg-like W LXIII

For this ion, earlier calculations for energy levels are by Safronova and Safronova [23] using the RMBPT method for the lowest 35 levels of the $3s^2$, $3s3p$, $3p^2$, $3s3d$, $3p3d$, and $3d^2$ configurations, whereas the NIST compilation is only for 9 levels – see Table I. As for other ions we have performed several sets of calculations with GRASP and FAC and here we only state our final results. For the GRASP calculations we have considered 58 configurations, which are $3\ell^2$, $3s3p$, $3s3d$, $3p3d$, $3\ell4\ell$, $4\ell^2$, $4\ell\ell'$, $3\ell5\ell$, and $3\ell6\ell$ (except 6h), while for FAC we include 991 levels, the additional ones arising from $3\ell7\ell$ and $4\ell5\ell$. However, levels of the $4\ell^2$, $4\ell\ell'$ and $4\ell5\ell$ configurations mostly lie above those of $3\ell7\ell$ and can therefore be neglected. Energy levels from both calculations are listed in Table 5 for the lowest 210 levels. In Table I a comparison is shown for the lowest 35 levels with the NIST compilation and the RMBPT calculations [23]. As for W LXII, the FAC and RMBPT energies agree closely with each other as well as with NIST, but our GRASP energies are higher by up to 0.3 Ryd for many levels. Similarly, mixing for the levels is strong for a few as shown

in Table J for the lowest 35 – see in particular levels 22, 25 and 34.

2.6. Na-like W LXIV

For this ion we have gradually increased the number of orbitals to perform GRASP calculations for up to 1235 levels. The configurations included are $2p^6n\ell$ with $n \leq 7$ and $\ell \leq 4$, $2p^53\ell\ell'$, $2p^53\ell^2$, $2p^54\ell\ell'$, $2p^54\ell^2$, and $2p^53\ell4\ell$. However, we note that the levels of $2p^6n\ell$ lie *below* those of the other configurations. For this reason we only list the lowest 30 levels in Table K, all belonging to $2p^6n\ell$. However, with FAC we have performed comparatively larger calculations for up to $n = 20$ and all possible values of ℓ , i.e. 1592 levels in total. These results are also listed in Table K along with those of NIST, which are confined to the $n \leq 5$ levels. The NIST energies differ with FAC by up to 0.26 Ryd for some levels (see 20), but discrepancies are smaller than 0.15 Ryd with those with GRASP. Again, the differences between the GRASP and FAC energies are not because of different levels of CI, but due to methodological variations. It has not been possible to include higher $2p^6n\ell$ configurations in our GRASP calculations, but since the FAC energies have been obtained (as stated above) in Table 6 we list these for the lowest 396 levels, all belonging to $2p^6n\ell$ with $n \leq 20$. This will be helpful for future comparisons. Finally, unlike the other W ions discussed above, there is no (strong) mixing and/or ambiguity for the designation of the $2p^6n\ell$ levels listed in Tables K and 6.

Safronova et al. [25] have reported energies for 242 levels of W LXIV from three independent codes, namely RMBPT, HULLAC (Hebrew University Lawrence Livermore Atomic Code [26]) and the atomic structure code of R.D. Cowan available at <http://das101.isan.troitsk.ru/cowan.htm>. Although NIST energies for this ion are only available for a few levels, as already seen in Table K, their RMBPT results are closest to the measurements. Additionally, based on the comparisons made for other W ions, their RMBPT energies should be the most accurate. Nevertheless, the RMBPT energy for level 2 ($2p^53s\ ^3P_2^o$) differs by 1.3% and 6.4% with those from HULLAC and Cowan, respectively. Corresponding differences for the remaining levels are up to 0.3% and 1%, respectively. Only the lowest 5 levels of Table K are common with their work, as the remaining 237 belong to the $2p^53\ell\ell'$ configurations. Therefore, our listed energies in Table 6 supplement their data.

2.7. Ne-like W LXV

The NIST compilation of energies for this ion is limited to only 10 levels of the $2p^53\ell$ configurations. However, Vilkas et al. [27] have reported energies for 141 levels of the $2p^6$, $(2s2p^6)3\ell$, 4ℓ , 5ℓ (except $5g$), and $(2p^5)\ 3\ell$, 4ℓ , 5ℓ (except $5g$) configurations. For their calculations they adopted the relativistic multi-reference many-body Møller-Plesset (MRMP) perturbation theory, and included CI up to the $n = 5$ orbitals. We have included the same configurations for our calculations with GRASP, which generate 157 levels in total because we have also considered the $5g$ orbital. However, in Table 7 we list energies for only the lowest 121, because beyond this the levels of the $2s2p^66\ell$ configurations start mixing in the same way as of $2s2p^65g$ with those of $2s2p^64\ell$ – see levels 92–99 in the table. Additionally, we have performed larger calculations with FAC with up to 1147 levels, belonging to the $2*8$, $(2*7)\ 3*1$, $4*1$, $5*1$, $6*1$, $7*1$, and $2*6\ 3*2$ configurations. These results are also listed in Table 7 for comparison. Differences between the GRASP and FAC energies are up to 0.5 Ryd (0.07%) for some levels, but the level orderings are almost identical. Similarly, there is no difference in level orderings with the MRMP calculations [27] and the energies differ only by less than 0.6 Ryd (0.06%) with GRASP – see levels 63 and 77–83. Therefore, overall there is no (significant) discrepancy between the three independent calculations. However, in general the FAC energies are lower than those from GRASP for a majority of levels, whereas those of MRMP are higher.

In Table L, we compare energies with the NIST compilation for only the *common* levels. There is no uniform pattern for (dis)agreement between the theoretical and experimental energies. In general, the MRMP energies are closer to those of NIST

whereas those from FAC differ the most. Unfortunately, these comparisons are not sufficient for accuracy determination, particularly when the NIST energies are not based on direct measurements. Finally, as for most W ions, for W LXV also there is a strong mixing for some levels and therefore the level designations listed in Table 7 can vary, although the MRMP calculations [27] have the same labels as in our work. Nevertheless, in Table M we list the eigenvectors for the lowest 33 levels, which include all of the NIST compilation. Note particularly the mixing for levels 24, 25 and 31.

2.8. *F-like W LXVI*

For this ion we have performed a series of calculations with GRASP with gradually increasing CI and our final set includes 501 levels of 38 configurations, which are: $2s^22p^5$, $2s2p^6$, $(2s^22p^4, 2s2p^5, 2p^6)3\ell, 4\ell, 5\ell$. Similarly, calculations with FAC have been performed for up to 1113 levels from the $2*7$ and $(2*6) 3*1, 4*1, 5*1, 6*1, 7*1$ configurations. These levels span an energy range of up to 1360 Ryd. Opening the $1s$ shell gives rise to levels above 5000 Ryd and therefore has not been included in the calculations. Energies from both of these calculations are listed in Table 8 for the lowest 150 levels, because beyond this the levels of the $n = 5$ configurations start mixing. However, the listed levels include all of the $n = 3$ configurations. Differences between the two sets of energies are up to 0.5 Ryd for some levels, except three (145–147) for which the discrepancies are slightly larger, up to 0.7 Ryd. The level orderings are also the same for a majority of levels, but slightly differ in a few instances, such as for 93–112. NIST listings are available for only two levels, namely $2s^22p^5 \ ^2P_{1/2}^o$ and $2s2p^6 \ ^2S_{1/2}$, and the energy for the latter is lower by 0.5 Ryd than the theoretical results. No other similar theoretical energies are available for this ion for comparison purposes. Finally, this ion is no exception for level mixing and examples of this are listed in Table N for the lowest 48 levels – see in particular 13, 15, 40, and 42.

3. Radiative rates

Apart from energy levels, calculations have been made for absorption oscillator strengths (f -values, dimensionless), radiative rates (A -values, s^{-1}) and line strengths (S -values, in atomic units, $1 \text{ a.u.} = 6.460 \times 10^{-36} \text{ cm}^2 \text{ esu}^2$). However, f - and A -values for all types of transition ($i \rightarrow j$) are connected by the following expression:

$$f_{ij} = \frac{mc}{8\pi^2 e^2} \lambda_{ji}^2 \frac{\omega_j}{\omega_i} A_{ji} = 1.49 \times 10^{-16} \lambda_{ji}^2 \frac{\omega_j}{\omega_i} A_{ji} \quad (1)$$

where m and e are the electron mass and charge, respectively, c the velocity of light, λ_{ji} the transition wavelength in Å, and ω_i and ω_j the statistical weights of the lower i and upper j levels, respectively. Similarly, f - and A -values are related to S by the standard equations given in [9].

In Tables 9–16 we present results for energies (wavelengths, λ_{ji} in Å), A -, f - and S - values for electric dipole (E1) transitions in W ions, which have been obtained with the GRASP code. For other types of transitions, namely magnetic dipole (M1), electric quadrupole (E2), and magnetic quadrupole (M2), only the A -values are listed, because the corresponding results for f - or S -values can be obtained using Eqs. (1-5) given in [9]. Additionally, we have also listed the ratio (R) of the velocity (Coulomb gauge) and length (Babushkin gauge) forms which often (but not necessarily) give an indication of the accuracy. The *indices* used to represent the lower and upper levels of a transition are defined in Tables 1–8. Furthermore, only a limited range of transitions are listed in Tables 9–16, but full tables are available online in the electronic version.

For the W ions considered here, existing A - (or f -) values are available mostly for three ions, i.e. Al-like W LXII [23], Mg-like W LXIII [23] and Na-like W LXIV [27]. Therefore, we confine our comparisons to these three ions. In Table O we compare the

f -values for common E1 transitions with the results of Safronova and Safronova [23]. Both sets of data agree very well for all transitions. Similarly, for a few weak transitions ($f \sim 10^{-4}$), such as 1–22, 2–3 and 14–19, the ratio R is up to 1.7 and is closer to unity for the comparatively strong transitions. Similar comparison with their results for transitions in W LXIII is shown in Table P. For the common transitions listed here, R is unity for all, and f -values agree closely for most with only a few exceptions, such as 20–32, 21–30 and 26–34 for which discrepancies are a factor of two. However, we note that the f - (or A -) values of [23] are only for a small number of transitions whereas our results listed in Tables 12 and 13 cover a much wider range.

Vilkas et al. [27] have listed A -values for some (not all) transitions of W LXV and in Table Q we compare their results with our calculations with GRASP, but only from the lowest three to higher excited levels. Additionally we have listed the f -values to indicate the strength of transitions. As for other W ions, R is also listed for these transitions and is within a few percent of unity, irrespective of the f -value. There are no appreciable differences between the two sets of A -values and discrepancies, if any, are (generally) within $\sim 20\%$.

The comparisons of A - (f -) values discussed above are only for a subset of transitions. Considering a wider range, for a majority of strong transitions ($f \geq 0.01$) R is often within 20% of unity, as already seen in Tables O, P and Q. However, there are (as always) some exceptions. For example, there are only six transitions of W LXIII with $f > 0.01$ for which R is up to 1.6, namely 148–166 ($f = 0.011$, $R = 1.3$), 158–173 ($f = 0.021$, $R = 1.3$), 160–174 ($f = 0.028$, $R = 1.6$), 161–175 ($f = 0.025$, $R = 1.4$), 162–176 ($f = 0.027$, $R = 1.4$), and 163–177 ($f = 0.029$, $R = 1.6$). Therefore, based on this and other comparisons already discussed, our assessment of accuracy for the f -values for a majority of strong transitions is $\sim 20\%$. Finally, for much weaker transitions (often with $f \leq 10^{-4}$), R can be several orders of magnitude and it is very difficult to assess the accuracy of the f -values because results are often much more variable with CI and/or codes. Generally, such transitions do not make an appreciable contribution to plasma modelling and their results are mostly required for completeness.

4. Lifetimes

The lifetime τ of a level j is given by $1.0/\sum_i A_{ji}$ and the summation includes A -values from all types of transitions, i.e. E1, E2, M1, and M2. Since this is a measurable quantity it helps to assess the accuracy of A -values, particularly when a single (type of) transition dominates. Unfortunately, to our knowledge no measurements of τ are available for the levels of the W ions considered here, but in Tables 1–8 we list our calculated results. Previous theoretical results are available for two ions, i.e. W LXII [12] and W LXV [27]. Unfortunately, the τ of S. Aggarwal et al. [12] contain large errors, by up to 14 orders of magnitude, for over 90% of the levels of W LXII and bear no relationship to the A -values, as already discussed [24]. For W LXV, the reported τ of Vilkas et al. [27] are included in Table 7, and there is no significant discrepancy for any level.

5. Conclusions

Energy levels and radiative rates for E1, E2, M1, and M2 transitions are reported for eight W ions (W LIX to W LXVI). A large number of levels are considered for each ion and the data sets reported here are significantly larger than available in the literature. For our calculations the GRASP code has been adopted, although FAC has also been utilised for the determination of energy levels to assess the importance of CI, larger than that considered in GRASP. It is concluded that CI beyond a certain level does not appreciably improve the level energies. Differences between the GRASP and FAC energies, and the available experimental and theoretical values, are often smaller than 0.5 Ryd, or equivalently the listed energy levels for all W ions are assessed to be accurate to

better than 1%, but scope remains for improvement. A similar assessment of accuracy for the corresponding A -values is not feasible, mainly because of the paucity of other comparable results. However, for strong transitions (with large f -values), the accuracy for A -values and lifetimes may be $\sim 20\%$. Lifetimes for these levels are also listed although no measurements are currently available in the literature. However, previous theoretical values are available for most levels of W LXV and there is no discrepancy with our work.

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Appendix A. Supplementary data

Owing to space limitations, only parts of Tables 9–16 are presented here, the full tables being made available as supplemental material in conjunction with the electronic publication of this work. Supplementary data associated with this article can be found, in the online version, at doi:nn.nnnn/j.adt.2016.nn.nnn.

References

- [1] T. Pütterich, R. Neu, R. Dux, A.D. Whiteford, M.G. O’Mullane and the ASDEX Upgrade Team, Plasma Phys. Cont. Fusion 50 (2008) 085016.
- [2] K. Fournier, At. Data Nucl. Data Tables 68 (1998) 1.
- [3] A.E. Kramida, T. Shirai, At. Data Nucl. Data Tables 95 (2009) 305+1051.
- [4] A. Kramida, Can J. Phys. 93 (2015) 487.
- [5] Y. Ralchenko, I.N. Draganic, J.N. Tan, J.D. Gillaspay, J.M. Poneroy, J. Reader, U. Feldman, G.E. Holland, J. Phys. B41 (2008) 021003.
- [6] J. Clementson, P. Beiersdorfer, G.V. Brown, M.F. Gu, H. Lundberg, Y. Podpaly, and E. Träbert. Can. J. Phys. **89**, 571 (2011).
- [7] P. Quinet, J. Phys. B44 (2011) 195007.
- [8] K.M. Aggarwal, F.P. Keenan, Can J. Phys. 92 (2014) 545.
- [9] K.M. Aggarwal, F.P. Keenan, At. Data Nucl. Data Tables 100 (2014) 1399.
- [10] K.M. Aggarwal, F.P. Keenan, Can J. Phys. 92 (2014) 1166.
- [11] K.M. Aggarwal, F.P. Keenan, At. Data Nucl. Data Tables 100 (2014) 1603.
- [12] S. Aggarwal, A.K.S. Jha, I. Khatri, N. Singh, M. Mohan, Chin. Phys. B24 (2015) 053201.
- [13] I.P. Grant, B.J. McKenzie, P.H. Norrington, D.F. Mayers, N.C. Pyper, Comput. Phys. Commun. 21 (1980) 207.
- [14] K.G. Dyall, I.P. Grant, C.T. Johnson, F.A. Parpia, E.P. Plummer, Comput. Phys. Commun. 55 (1989) 425.
- [15] P. Jönsson, X. He, C.F. Fischer, I.P. Grant, Comput. Phys. Commun. 177 (2007) 597.
- [16] P. Jönsson, G. Gaigalas, J. Bieroń, C.F. Fischer, I.P. Grant, Comput. Phys. Commun. 184 (2013) 2197.

- [17] K.M. Aggarwal, F.P. Keenan, K.D. Lawson, *At. Data Nucl. Data Tables* 94 (2008) 323.
- [18] K.M. Aggarwal, F.P. Keenan, K.D. Lawson, *At. Data Nucl. Data Tables* 96 (2010) 123.
- [19] J. Clementson, P. Beiersdorfer, *Phys. Rev. A* 81 (2010) 052509.
- [20] U. Feldman, J.F. Seely, E. Landi, Yu. Ralchenko, *Nucl. Fusion* 48 (2008) 045004.
- [21] M.F. Gu, *Can. J. Phys.* 86 (2008) 675.
- [22] K.M. Aggarwal, V. Tayal, G.P. Gupta, F.P. Keenan, *At. Data Nucl. Data Tables* 93 (2007) 615.
- [23] U.I. Safronova, A.S. Safronova, *J. Phys. B* 43 (2010) 074026.
- [24] K.M. Aggarwal, *Chin. Phys. B* 24 (2015) 103201.
- [25] U.I. Safronova, A.S. Safronova, P. Beiersdorfer, *At. Data Nucl. Data Tables* 95 (2009) 751.
- [26] A. Bar-Shalom, M. Klapisch, J. Oreg, *J. Quant. Spectrosc. Radiat. Transfer* 71 (2001) 169.
- [27] M.J. Vilkas, J.M. López-Encarnación, Y. Ishikawa, *At. Data Nucl. Data Tables* 94 (2008) 50.

Table A

Comparison of threshold energies (in Ryd) for the lowest 20 levels of W LIX.

Index	Configuration	Level	NIST	GRASP1	GRASP2	FAC1	FAC2
1	3s ² 3p ⁴	³ P ₂	00.0000	0.0000	0.0000	0.00000	0.0000
2	3s ² 3p ⁴	¹ S ₀	01.394	1.4629	1.4691	1.46006	1.4675
3	3s ² 3p ³ (⁴ S)3d	⁵ D ₂ ^o	17.2585	17.3063	17.2920	17.23239	17.2200
4	3s ² 3p ³ (² D)3d	³ P ₀ ^o	17.852	17.9536	17.9413	17.85940	17.8689
5	3s ² 3p ³ (⁴ S)3d	⁵ D ₁ ^o	17.852	17.9342	17.9213	17.87821	17.8489
6	3s ² 3p ³ (² P)3d	³ F ₃ ^o	17.9173	17.9812	17.9637	17.90613	17.8913
7	3s ² 3p ³ (² D)3d	¹ G ₄ ^o	23.4589	23.4945	23.4758	23.42838	23.4095
8	3s ² 3p ³ (² D)3d	³ D ₂ ^o	23.94	23.9785	23.9637	23.91315	23.8975
9	3s ² 3p ³ (⁴ S)3d	⁵ D ₃ ^o	25.29	25.4172	25.3923	25.35176	25.3264
10	3s ² 3p ⁴	³ P ₁		25.4932	25.4899	25.52002	25.5134
11	3s ² 3p ³ (² D)3d	³ P ₁ ^o	25.96	26.2537	26.2281	26.18601	26.1616
12	3s ² 3p ⁴	¹ D ₂		26.2096	26.2037	26.23460	26.2258
13	3s ² 3p ² (¹ S)3d ² (³ F)	³ F ₂		35.3490	35.3341	35.19957	35.1818
14	3s ² 3p ² (³ P)3d ² (³ P)	⁵ D ₀		37.1186	37.1256	36.96614	36.9719
15	3s3p ⁵	³ P ₂ ^o	39.0268	39.1209	39.1426	39.03447	39.0438
16	3s3p ⁵	¹ P ₁ ^o	40.62	40.6371	40.6465	40.56564	40.5641
17	3s ² 3p ² (¹ S)3d ² (³ F)	³ F ₃		41.8457	41.8247	41.70542	41.6775
18	3s ² 3p ³ (² D)3d	³ F ₂ ^o	42.43	42.0799	42.0634	42.03196	42.0150
19	3s ² 3p ³ (⁴ S)3d	⁵ D ₀ ^o	42.53	42.1816	42.1679	42.13380	42.1196
20	3s ² 3p ³ (² D)3d	³ D ₁ ^o	42.60	42.2933	42.2833	42.23549	42.2231

NIST: <http://www.nist.gov/pml/data/asd.cfm>

GRASP1: Present results with the GRASP code from 18 configurations and 2762 levels

GRASP2: Present results with the GRASP code from 46 configurations and 12 652 levels

FAC1: Present results with the FAC code from 2762 levels

FAC2: Present results with the FAC code from 38 694 levels

Table B

Eigenvectors (EV) for the lowest 20 levels of W LIX from the GRASP code. Numbers outside and inside a bracket correspond to EV and the level, respectively. See Table 1 for the definition of all levels.

Index	Configuration	Level	Eigenvectors
1	3s ² 3p ⁴	³ P ₂	0.67(1)+0.31(12)
2	3s ² 3p ⁴	¹ S ₀	0.36(46)+0.64(2)
3	3s ² 3p ³ (⁴ S)3d	⁵ D ₂ ^o	0.16(3)+0.08(41)+0.19(18)+0.06(45)+0.10(26)+0.23(108)+0.12(132)
4	3s ² 3p ³ (² D)3d	³ P ₀ ^o	0.26(19)+0.14(4)+0.12(37)+0.48(105)
5	3s ² 3p ³ (⁴ S)3d	⁵ D ₁ ^o	0.24(5)+0.14(20)+0.10(43)+0.18(30)+0.27(107)
6	3s ² 3p ³ (² P)3d	³ F ₃ ^o	0.13(9)+0.12(106)+0.21(22)+0.05(44)+0.27(6)+0.06(136)+0.14(40)
7	3s ² 3p ³ (² D)3d	¹ G ₄ ^o	0.26(32)+0.14(25)+0.10(7)+0.48(130)
8	3s ² 3p ³ (² D)3d	³ D ₂ ^o	0.10(3)+0.14(41)+0.16(8)+0.07(28)+0.04(108)+0.22(39)+0.19(132)
9	3s ² 3p ³ (⁴ S)3d	⁵ D ₃ ^o	0.14(9)+0.09(106)+0.06(22)+0.17(27)+0.30(136)+0.17(40)
10	3s ² 3p ⁴	³ P ₁	0.98(10)
11	3s ² 3p ³ (² D)3d	³ P ₁ ^o	0.22(35)+0.14(11)+0.08(29)+0.09(30)+0.14(107)+0.24(147)
12	3s ² 3p ⁴	¹ D ₂	0.31(1)+0.67(12)
13	3s ² 3p ² (¹ S)3d ² (³ F)	³ F ₂	0.23(59)+0.06(88)+0.10(96)+0.05(285)+0.05(350)+0.08(38)+0.06(277)+0.22(13)+0.07(325)
14	3s ² 3p ² (³ P)3d ² (³ P)	⁵ D ₀	0.28(14)+0.16(85)+0.04(114)+0.21(42)+0.21(371)+0.10(342)
15	3s3p ⁵	³ P ₂ ^o	0.07(28)+0.85(15)
16	3s3p ⁵	¹ P ₁ ^o	0.12(5)+0.05(11)+0.11(43)+0.24(86)+0.36(16)
17	3s ² 3p ² (¹ S)3d ² (³ F)	³ F ₃	0.23(57)+0.16(221)+0.05(262)+0.08(87)+0.10(139)+0.05(282)+0.30(17)
18	3s ² 3p ³ (² D)3d	³ F ₂ ^o	0.29(3)+0.10(41)+0.40(18)+0.13(8)+0.04(26)
19	3s ² 3p ³ (⁴ S)3d	⁵ D ₀ ^o	0.53(19)+0.21(4)+0.24(37)
20	3s ² 3p ³ (² D)3d	³ D ₁ ^o	0.32(5)+0.05(35)+0.40(20)+0.07(11)+0.06(86)+0.05(16)

Table C

Comparison of threshold energies (in Ryd) for the lowest 25 levels of W LX.

Index	Configuration	Level	NIST	GRASP1	GRASP2	FAC1	FAC2
1	$3s^2 3p^3$	$2D_{3/2}^o$	00.0000	0.0000	0.0000	0.0000	0.0000
2	$3s^2 3p^2(^3P)3d$	$4F_{3/2}$	16.8821	16.9403	16.9357	16.8671	16.8529
3	$3s^2 3p^2(^1S)3d$	$2D_{5/2}$	23.903	23.8688	23.8613	23.8040	23.7839
4	$3s^2 3p^3$	$4S_{3/2}^o$	25.060	25.0648	25.0619	25.0905	25.0865
5	$3s^2 3p^3$	$2D_{5/2}^o$	25.9556	25.9490	25.9411	25.9727	25.9639
6	$3s^2 3p^3$	$2P_{1/2}^o$	27.019	27.0845	27.0831	27.1065	27.1049
7	$3s 3p^4$	$4P_{5/2}$	37.9315	37.9970	38.0129	37.9087	37.9134
8	$3s 3p^4$	$2P_{3/2}$	40.242	40.1880	40.1973	40.1132	40.1082
9	$3s 3p^4$	$2S_{1/2}$	40.205	40.3454	40.3636	40.2582	40.2632
10	$3s^2 3p^2(^3P)3d$	$4F_{5/2}$	42.01	41.8139	41.8076	41.7643	41.7479
11	$3s^2 3p^2(^3P)3d$	$4D_{1/2}$	42.16	42.0470	42.0473	41.9973	41.9888
12	$3s^2 3p^2(^3P)3d$	$4D_{3/2}$	42.24	42.0827	42.0820	42.0263	42.0159
13	$3s^2 3p^2(^1D)3d$	$2G_{7/2}$	42.97	42.7366	42.7255	42.6856	42.6644
14	$3s^2 3p^2(^3P)3d$	$2D_{5/2}$	44.848	44.9721	44.9564	44.9235	44.8978
15	$3s^2 3p^2(^1D)3d$	$2P_{1/2}$	45.51	45.7510	45.7334	45.6952	45.6683
16	$3s^2 3p^2(^1D)3d$	$2D_{3/2}$	45.6572	45.8196	45.8091	45.7563	45.7341
17	$3s^2 3p^2(^3P)3d$	$4F_{7/2}$	47.96	47.7759	47.7717	47.7352	47.7188
18	$3s^2 3p^2(^3P)3d$	$2P_{3/2}$	48.90	48.7073	48.7034	48.6656	48.6501
19	$3s^2 3p^2(^1D)3d$	$2G_{9/2}$	48.98	48.7536	48.7404	48.7119	48.6861
20	$3s^2 3p^2(^3P)3d$	$2F_{5/2}$	49.19	48.9732	48.9665	48.9329	48.9141
21	$3s^2 3p^2(^3P)3d$	$4P_{5/2}$	50.74	50.5135	50.4973	50.4698	50.4412
22	$3s^2 3p^2(^1D)3d$	$2F_{7/2}$	50.87	50.5992	50.5800	50.5583	50.5262
23	$3s^2 3p^2(^3P)3d$	$2D_{3/2}$	51.38	51.2398	51.2202	51.1970	51.1682
24	$3s^2 3p^2(^1D)3d$	$2S_{1/2}$	51.67	51.5331	51.5132	51.4871	51.4582
25	$3s^2 3p^3$	$2P_{3/2}^o$	52.18	52.2859	52.2799	52.3345	52.3257

NIST: <http://www.nist.gov/pml/data/asd.cfm>

GRASP1: Present results with the GRASP code from 15 configurations and 1313 levels

GRASP2: Present results with the GRASP code from 35 configurations and 3533 levels

FAC1: Present results with the FAC code from 1313 levels

FAC2: Present results with the FAC code from 14 608 levels

Table D

Eigenvectors (EV) for the lowest 25 levels of W LX from the GRASP code. Numbers outside and inside a bracket correspond to EV and the level, respectively. See Table 2 for the definition of all levels.

Index	Configuration	Level	Eigenvectors
1	$3s^2 3p^3$	$2D_{3/2}^o$	0.25(4)+0.27(1)+0.48(25)
2	$3s^2 3p^2(^3P)3d$	$4F_{3/2}$	0.34(2)+0.12(12)+0.10(23)+0.11(18)+0.31(60)
3	$3s^2 3p^2(^1S)3d$	$2D_{5/2}$	0.17(10)+0.20(57)+0.14(21)+0.15(20)+0.30(3)
4	$3s^2 3p^3$	$4S_{3/2}^o$	0.55(4)+0.45(1)
5	$3s^2 3p^3$	$2D_{5/2}^o$	1.00(5)
6	$3s^2 3p^3$	$2P_{1/2}^o$	0.98(6)
7	$3s3p^4$	$4P_{5/2}$	0.66(7)+0.27(45)
8	$3s3p^4$	$2P_{3/2}$	0.08(2)+0.06(58)+0.11(18)+0.06(16)+0.11(41)+0.32(8)+0.24(51)
9	$3s3p^4$	$2S_{1/2}$	0.05(59)+0.07(24)+0.24(137)+0.07(48)+0.53(9)
10	$3s^2 3p^2(^3P)3d$	$4F_{5/2}$	0.46(10)+0.16(20)+0.29(74)
11	$3s^2 3p^2(^3P)3d$	$4D_{1/2}$	0.79(11)+0.04(59)+0.14(70)
12	$3s^2 3p^2(^3P)3d$	$4D_{3/2}$	0.32(2)+0.28(12)+0.12(18)+0.12(16)+0.05(73)+0.04(51)
13	$3s^2 3p^2(^1D)3d$	$2G_{7/2}$	0.18(17)+0.14(56)+0.53(13)+0.12(22)
14	$3s^2 3p^2(^3P)3d$	$2D_{5/2}$	0.10(10)+0.10(57)+0.12(21)+0.30(14)+0.24(74)+0.06(72)
15	$3s^2 3p^2(^1D)3d$	$2P_{1/2}$	0.30(59)+0.35(15)+0.18(24)+0.08(9)
16	$3s^2 3p^2(^1D)3d$	$2D_{3/2}$	0.22(58)+0.08(18)+0.26(16)+0.14(73)+0.13(8)+0.07(51)
17	$3s^2 3p^2(^3P)3d$	$4F_{7/2}$	0.37(17)+0.48(67)+0.07(56)+0.07(22)
18	$3s^2 3p^2(^3P)3d$	$2P_{3/2}$	0.16(12)+0.23(58)+0.05(23)+0.25(18)+0.06(16)+0.20(73)
19	$3s^2 3p^2(^1D)3d$	$2G_{9/2}$	0.37(69)+0.62(19)
20	$3s^2 3p^2(^3P)3d$	$2F_{5/2}$	0.04(10)+0.22(57)+0.07(21)+0.32(20)+0.04(74)+0.25(72)
21	$3s^2 3p^2(^3P)3d$	$4P_{5/2}$	0.35(21)+0.10(20)+0.14(14)+0.08(74)+0.27(72)
22	$3s^2 3p^2(^1D)3d$	$2F_{7/2}$	0.17(17)+0.05(67)+0.18(56)+0.15(13)+0.44(22)
23	$3s^2 3p^2(^3P)3d$	$2D_{3/2}$	0.05(2)+0.11(12)+0.46(23)+0.14(16)+0.22(73)
24	$3s^2 3p^2(^1D)3d$	$2S_{1/2}$	0.31(70)+0.23(15)+0.36(24)
25	$3s^2 3p^3$	$2P_{3/2}^o$	0.19(4)+0.28(1)+0.50(25)

Table E

Comparison of threshold energies (in Ryd) for the lowest 21 levels of W LXI.

Index	Configuration	Level	NIST	GRASP1	GRASP2	FAC1	FAC2
1	3s ² 3p ²	³ P ₀	00.0000	00.0000	0.0000	0.0000	0.0000
2	3s ² 3p ²	³ P ₁	25.5337	25.5392	25.5395	25.5650	25.5675
3	3s ² 3p ²	¹ D ₂	26.2946	26.2402	26.2351	26.2574	26.2587
4	3s3p ³	⁵ S ₂ ^o	38.2094	38.0581	38.0606	37.9699	37.9709
5	3s3p ³	³ D ₁ ^o	39.9800	40.1129	40.1071	40.0211	40.0210
6	3s ² 3p3d	³ F ₂ ^o		41.7903	41.7744	41.7215	41.7222
7	3s ² 3p3d	³ D ₁ ^o		45.1086	45.0826	45.0158	45.0129
8	3s ² 3p3d	³ P ₂ ^o	49.57	49.1925	49.1738	49.1246	49.1247
9	3s ² 3p3d	³ F ₃ ^o	49.65	49.2768	49.2540	49.2059	49.2052
10	3s ² 3p ²	³ P ₂	52.27	52.3039	52.2993	52.3463	52.3487
11	3s ² 3p ²	¹ S ₀	53.71	53.8224	53.8202	53.8658	53.8642
12	3s3p ² (⁴ P)3d	⁵ F ₁		54.6247	54.6092	54.4384	54.4378
13	3s3p ² (⁴ P)3d	³ P ₂		55.1766	55.1588	54.9863	54.9850
14	3s3p ² (⁴ P)3d	⁵ P ₃		61.6560	61.6353	61.4690	61.4679
15	3s3p ² (⁴ P)3d	³ F ₂		62.7077	62.6817	62.5113	62.5082
16	3s3p ³	³ D ₂ ^o	63.01	62.9640	62.9654	62.9020	62.9054
17	3s3p ³	³ D ₃ ^o	64.46	64.3393	64.3357	64.2689	64.2712
18	3s3p ³	³ P ₀ ^o	65.29	65.1798	65.1832	65.1238	65.1237
19	3s3p ³	³ P ₁ ^o	66.52	66.2880	66.2870	66.2268	66.2275
20	3s3p ³	¹ D ₂ ^o	66.51	66.2776	66.2699	66.2141	66.2160
21	3s3p ³	³ S ₁ ^o	67.24	67.1867	67.1794	67.1047	67.1036

NIST: <http://www.nist.gov/pml/data/asd.cfm>

GRASP1: Present results with the GRASP code from 12 configurations and 518 levels

GRASP2: Present results with the GRASP code from 48 configurations and 4364 levels

FAC1: Present results with the FAC code from 9798 levels

FAC2: Present results with the FAC code from 27 122 levels

Table FEigenvectors (EV) for the lowest 21 (plus ³P₂^o and ¹P₀^o of 3s3p³) levels of W LXI from the GRASP code. Numbers outside and inside a bracket correspond to EV and the level, respectively. See Table 3 for the definition of all levels.

Index	Configuration	Level	Eigenvectors
1	3s ² 3p ²	³ P ₀	0.69(1)+0.31(11)
2	3s ² 3p ²	³ P ₁	1.00(2)
3	3s ² 3p ²	¹ D ₂	0.35(10)+0.64(3)
4	3s3p ³	⁵ S ₂ ^o	0.27(4)+0.16(16)+0.08(20)+0.46(64)
5	3s3p ³	³ D ₁ ^o	0.14(21)+0.28(5)+0.16(19)+0.24(69)+0.09(7)+0.05(29)
6	3s ² 3p3d	³ F ₂ ^o	0.74(6)+0.19(27)
7	3s ² 3p3d	³ D ₁ ^o	0.04(21)+0.04(5)+0.05(69)+0.44(7)+0.14(24)+0.25(29)
8	3s ² 3p3d	³ P ₂ ^o	0.34(23)+0.45(8)+0.14(27)
9	3s ² 3p3d	³ F ₃ ^o	0.50(9)+0.22(28)+0.26(22)
10	3s ² 3p ²	³ P ₂	0.64(10)+0.35(3)
11	3s ² 3p ²	¹ S ₀	0.30(1)+0.67(11)
12	3s3p ² (⁴ P)3d	⁵ F ₁	0.38(12)+0.07(32)+0.05(57)+0.08(42)+0.05(137)+0.30(110)
13	3s3p ² (⁴ P)3d	³ P ₂	0.18(30)+0.11(105)+0.08(134)+0.12(13)+0.12(45)+0.21(113)+0.09(135)
14	3s3p ² (⁴ P)3d	⁵ P ₃	0.13(33)+0.19(106)+0.15(14)+0.04(49)+0.08(60)+0.05(116)+0.30(132)
15	3s3p ² (⁴ P)3d	³ F ₂	0.09(30)+0.05(105)+0.25(15)+0.07(134)+0.08(119)+0.07(63)+0.09(113)+0.21(135)
16	3s3p ³	³ D ₂ ^o	0.45(4)+0.49(16)
17	3s3p ³	³ D ₃ ^o	0.94(17)
18	3s3p ³	³ P ₀ ^o	0.86(18)+0.14(25)
19	3s3p ³	³ P ₁ ^o	0.18(21)+0.20(5)+0.34(19)+0.12(69)+0.04(7)+0.12(24)
20	3s3p ³	¹ D ₂ ^o	0.08(4)+0.08(16)+0.55(20)+0.07(6)+0.12(23)+0.08(27)
21	3s3p ³	³ S ₁ ^o	0.32(21)+0.20(5)+0.26(19)+0.18(69)
...			
64	3s3p ³	³ P ₂ ^o	0.17(4)+0.16(16)+0.14(20)+0.50(64)
69	3s3p ³	¹ P ₀ ^o	0.23(21)+0.23(5)+0.14(19)+0.35(69)

Table G

Comparison of threshold energies (in Ryd) for the lowest 21 levels of W LXII.

Index	Configuration	Level	NIST	GRASP2	GRASP3	FAC1	FAC2	RMBPT
1	3s ² 3p	² P _{1/2} ^o	00.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2	3s3p ²	⁴ P _{1/2}	12.3076	12.4425	12.4422	12.3220	12.3204	12.3018
3	3s ² 3p	² P _{3/2} ^o	26.7311	26.7061	26.7060	26.7306	26.7314	26.7056
4	3s3p ²	⁴ P _{3/2}	36.7742	36.8823	36.8835	36.7935	36.7959	36.7790
5	3s3p ²	² D _{5/2}	38.109	38.2380	38.2375	38.1447	38.1457	38.1110
6	3s3p ²	² D _{3/2}	39.6875	39.7869	39.7857	39.7028	39.7033	39.6637
7	3s3p ²	² P _{1/2}	40.4238	40.5824	40.5806	40.4826	40.4819	40.4024
8	3s ² 3d	² D _{3/2}	43.9039	44.0171	44.0103	43.9482	43.9448	43.8775
9	3s ² 3d	² D _{5/2}	49.263	49.3268	49.3215	49.2778	49.2759	49.2626
10	3p ³	² D _{3/2} ^o		51.9171	51.9167	51.7504	51.7496	51.7270
11	3s3p3d	⁴ F _{3/2} ^o		52.9289	52.9278	52.7221	52.7218	52.6746
12	3s3p3d	⁴ F _{5/2} ^o		53.7715	53.7680	53.5988	53.5989	53.5817
13	3s3p3d	⁴ D _{1/2} ^o		55.7589	55.7524	55.5868	55.5849	55.5323
14	3s3p3d	⁴ D _{3/2} ^o		56.2688	56.2632	56.0908	56.0883	56.0220
15	3s3p3d	⁴ P _{5/2} ^o		59.7857	59.7835	59.6243	59.6251	59.6240
16	3s3p3d	⁴ F _{7/2} ^o		60.8471	60.8418	60.6804	60.6797	60.6611
17	3s3p(³ P)3d	² F _{5/2} ^o		61.6177	61.6112	61.4480	61.4457	61.4177
18	3s3p(³ P)3d	² D _{3/2} ^o		62.0001	61.9931	61.8237	61.8206	61.7773
19	3s3p ²	⁴ P _{5/2}	64.372	64.4986	64.4980	64.4306	64.4321	64.3709
20	3s3p ²	² S _{1/2}	67.115	67.2861	67.2849	67.2135	67.2094	67.1156
21	3p ² (³ P)3d	⁴ F _{3/2}	67.479	67.8062	67.8002	67.3757	67.3714	67.4809

NIST: <http://www.nist.gov/pml/data/asd.cfm>

GRASP2: Present results with the GRASP code from 33 configurations and 928 levels

GRASP3: Present results with the GRASP code from 63 configurations and 2003 levels

FAC1: Present results with the FAC code from 2003 levels

FAC2: Present results with the FAC code from

RMBPT: Earlier results of Safronova and Safronova [23]

Table H

Eigenvectors (EV) for the lowest 21 (plus 68) levels of W LXII from the GRASP code. Numbers outside and inside a bracket correspond to EV and the level, respectively. See Table 4 for the definition of all levels.

Index	Configuration	Level	Eigenvectors
1	$3s^2 3p$	$2P_{1/2}^o$	1.00(1)
2	$3s 3p^2$	$4P_{1/2}$	0.52(2)+0.17(7)+0.30(20)
3	$3s^2 3p$	$2P_{3/2}^o$	0.98(3)
4	$3s 3p^2$	$4P_{3/2}$	0.88(4)+0.08(6)
5	$3s 3p^2$	$2D_{5/2}$	0.37(19)+0.61(5)
6	$3s 3p^2$	$2D_{3/2}$	0.28(22)+0.49(6)+0.18(8)
7	$3s 3p^2$	$2P_{1/2}$	0.29(2)+0.69(7)
8	$3s^2 3d$	$2D_{3/2}$	0.08(22)+0.12(6)+0.79(8)
9	$3s^2 3d$	$2D_{5/2}$	0.96(9)
10	$3p^3$	$2D_{3/2}^o$	0.23(11)+0.11(18)+0.06(37)+0.12(25)+0.16(10)+0.26(68)
11	$3s 3p 3d$	$4F_{3/2}^o$	0.55(11)+0.10(31)+0.07(25)+0.08(10)+0.14(68)
12	$3s 3p 3d$	$4F_{5/2}^o$	0.42(12)+0.07(17)+0.18(35)+0.24(32)
13	$3s 3p 3d$	$4D_{1/2}^o$	0.58(13)+0.06(28)+0.10(39)+0.26(33)
14	$3s 3p 3d$	$4D_{3/2}^o$	0.32(14)+0.18(27)+0.20(37)+0.13(31)+0.05(40)+0.04(68)
15	$3s 3p 3d$	$4P_{5/2}^o$	0.11(12)+0.31(29)+0.38(15)+0.07(17)+0.08(35)
16	$3s 3p 3d$	$4F_{7/2}^o$	0.42(16)+0.23(30)+0.08(36)+0.26(38)
17	$3s 3p(^3P) 3d$	$2F_{5/2}^o$	0.13(12)+0.12(15)+0.46(17)+0.05(32)+0.21(41)
18	$3s 3p(^3P) 3d$	$2D_{3/2}^o$	0.11(14)+0.05(27)+0.35(18)+0.16(37)+0.20(40)
19	$3s 3p^2$	$4P_{5/2}$	0.61(19)+0.38(5)
20	$3s 3p^2$	$2S_{1/2}$	0.18(2)+0.14(7)+0.67(20)
21	$3p^2(^3P) 3d$	$4F_{3/2}$	0.06(22)+0.04(6)+0.30(21)+0.10(43)+0.08(59)+0.10(99)+0.27(93)
...			
68	$3p^3$	$2P_{3/2}^o$	0.19(25)+0.28(10)+0.50(68)

Table I

Comparison of threshold energies (in Ryd) for the lowest 35 levels of W LXIII.

Index	Configuration	Level	NIST	GRASP	FAC	RMBPT
1	3s ²	¹ S ₀	00.0000	0.0000	0.0000	0.0000
2	3s3p	³ P ₀ ^o	10.261	10.3595	10.2414	10.2650
3	3s3p	³ P ₁ ^o	11.4036	11.5247	11.4028	11.4104
4	3p ²	³ P ₀		24.7520	24.5032	24.4911
5	3s3p	³ P ₂ ^o	37.398	37.4521	37.3609	37.3992
6	3s3p	¹ P ₁ ^o	40.0821	40.2273	40.1296	40.1225
7	3p ²	¹ D ₂		50.6187	50.4140	50.4418
8	3p ²	³ P ₁		50.7934	50.5757	50.5885
9	3s3d	³ D ₁	53.100	53.2554	53.0898	53.0968
10	3s3d	³ D ₂	54.0418	54.2279	54.0506	54.0421
11	3s3d	³ D ₃	59.214	59.3590	59.1988	59.2129
12	3s3d	¹ D ₂	60.490	60.6497	60.4812	60.4926
13	3p3d	³ F ₂ ^o		64.4267	64.1328	64.1616
14	3p3d	³ D ₁ ^o		67.0032	66.7097	66.6958
15	3p3d	³ P ₂ ^o		71.9267	71.6393	71.6688
16	3p3d	³ F ₃ ^o		72.1483	71.8606	71.8875
17	3p ²	³ P ₂		78.4319	78.2413	78.2584
18	3p ²	¹ S ₀		79.8512	79.6567	79.6637
19	3p3d	³ D ₂ ^o		92.4948	92.2324	92.2537
20	3p3d	³ P ₀ ^o		93.2392	92.9761	92.9927
21	3p3d	³ P ₁ ^o		93.2818	93.0183	93.0311
22	3p3d	¹ F ₃ ^o		93.2541	92.9898	92.9946
23	3p3d	³ F ₄ ^o		97.7310	97.4746	97.5357
24	3p3d	¹ D ₂ ^o		98.6141	98.3571	98.4030
25	3p3d	³ D ₃ ^o		100.0066	99.7469	99.7687
26	3p3d	¹ P ₁ ^o		100.9429	100.6812	100.6989
27	3d ²	³ F ₂		107.5330	107.1956	107.2079
28	3d ²	³ P ₀		109.5116	109.1710	109.1670
29	3d ²	³ F ₃		113.3167	112.9856	113.0263
30	3d ²	³ P ₂		114.2228	113.8902	113.9201
31	3d ²	¹ G ₄		114.3842	114.0519	114.0755
32	3d ²	³ P ₁		114.6216	114.2887	114.3189
33	3d ²	³ F ₄		119.7747	119.4490	119.5071
34	3d ²	¹ D ₂		120.5499	120.2230	120.2754
35	3d ²	¹ S ₀		122.6951	122.3631	122.3938

NIST: <http://www.nist.gov/pml/data/asd.cfm>

GRASP: Present results with the GRASP code from 58 configurations and 509 levels

FAC: Present results with the FAC code from 991 levels

RMBPT: Earlier results of Safronova and Safronova [23]

Table J

Eigenvectors (EV) for the lowest 35 levels of W LXIII from the GRASP code. Numbers outside and inside a bracket correspond to EV and the level, respectively. See Table 5 for the definition of all levels.

Index	Configuration	Level	Eigenvectors
1	3s ²	¹ S ₀	1.00(1)
2	3s3p	³ P ₀ ^o	1.00(2)
3	3s3p	³ P ₁ ^o	0.72(3)+0.27(6)
4	3p ²	³ P ₀	0.69(4)+0.30(18)
5	3s3p	³ P ₂ ^o	1.00(5)
6	3s3p	¹ P ₁ ^o	0.27(3)+0.72(6)
7	3p ²	¹ D ₂	0.28(17)+0.56(7)+0.05(10)+0.12(12)
8	3p ²	³ P ₁	1.00(8)
9	3s3d	³ D ₁	1.00(9)
10	3s3d	³ D ₂	0.06(17)+0.07(7)+0.69(10)+0.18(12)
11	3s3d	³ D ₃	1.00(11)
12	3s3d	¹ D ₂	0.26(10)+0.69(12)
13	3p3d	³ F ₂ ^o	0.76(13)+0.20(24)
14	3p3d	³ D ₁ ^o	0.53(14)+0.18(21)+0.29(26)
15	3p3d	³ P ₂ ^o	0.35(19)+0.48(15)+0.14(24)
16	3p3d	³ F ₃ ^o	0.52(16)+0.22(25)+0.26(22)
17	3p ²	³ P ₂	0.64(17)+0.36(7)
18	3p ²	¹ S ₀	0.31(4)+0.69(18)
19	3p3d	³ D ₂ ^o	0.19(13)+0.52(19)+0.04(15)+0.25(24)
20	3p3d	³ P ₀ ^o	1.00(20)
21	3p3d	³ P ₁ ^o	0.36(14)+0.59(21)+0.04(26)
22	3p3d	¹ F ₃ ^o	0.48(16)+0.18(25)+0.35(22)
23	3p3d	³ F ₄ ^o	1.00(23)
24	3p3d	¹ D ₂ ^o	0.11(19)+0.46(15)+0.40(24)
25	3p3d	³ D ₃ ^o	0.61(25)+0.38(22)
26	3p3d	¹ P ₁ ^o	0.11(14)+0.23(21)+0.66(26)
27	3d ²	³ F ₂	0.74(27)+0.23(34)
28	3d ²	³ P ₀	0.71(28)+0.30(35)
29	3d ²	³ F ₃	1.00(29)
30	3d ²	³ P ₂	0.21(27)+0.49(30)+0.30(34)
31	3d ²	¹ G ₄	0.29(33)+0.71(31)
32	3d ²	³ P ₁	1.00(32)
33	3d ²	³ F ₄	0.71(33)+0.29(31)
34	3d ²	¹ D ₂	0.06(27)+0.48(30)+0.46(34)
35	3d ²	¹ S ₀	0.30(28)+0.69(35)

Table KThreshold energies (in Ryd) of the lowest 30 levels of W LXIV and their lifetimes. ($a \pm b \equiv a \times 10^{\pm b}$).

Index	Configuration	Level	NIST	GRASP	FAC	τ (s)
1	2p ⁶ 3s	² S _{1/2}	000.0	0.0000	0.0000
2	2p ⁶ 3p	² P _{1/2} ^o	011.7280	11.8989	11.7457	2.218–11
3	2p ⁶ 3p	² P _{3/2} ^o	039.1890	39.3365	39.2218	5.664–13
4	2p ⁶ 3d	² D _{3/2}	052.9692	53.1127	52.9352	6.986–13
5	2p ⁶ 3d	² D _{5/2}	059.2105	59.3372	59.1730	4.987–12
6	2p ⁶ 4s	² S _{1/2}	239.12	239.0661	238.9973	1.501–14
7	2p ⁶ 4p	² P _{1/2} ^o	243.92	243.9788	243.8505	1.267–14
8	2p ⁶ 4p	² P _{3/2} ^o	255.18	255.2154	255.0981	2.010–14
9	2p ⁶ 4d	² D _{3/2}	260.37	260.4510	260.3002	8.821–15
10	2p ⁶ 4d	² D _{5/2}	263.09	263.1426	262.9954	8.466–15
11	2p ⁶ 4f	² F _{5/2} ^o	265.94	265.8618	265.7361	4.087–15
12	2p ⁶ 4f	² F _{7/2} ^o	267.12	267.0446	266.9176	4.198–15
13	2p ⁶ 5s	² S _{1/2}		345.5593	345.3305	1.888–14
14	2p ⁶ 5p	² P _{1/2} ^o		348.0234	347.7664	1.600–14
15	2p ⁶ 5p	² P _{3/2} ^o		353.6728	353.4209	2.398–14
16	2p ⁶ 5d	² D _{3/2}		356.2383	355.9695	1.189–14
17	2p ⁶ 5d	² D _{5/2}	357.54	357.6240	357.3573	1.168–14
18	2p ⁶ 5f	² F _{5/2} ^o	358.84	358.9640	358.7180	7.736–15
19	2p ⁶ 5f	² F _{7/2} ^o	359.46	359.5722	359.3256	7.962–15
20	2p ⁶ 5g	² G _{7/2}	359.77	359.7585	359.5057	1.361–14
21	2p ⁶ 5g	² G _{9/2}	360.11	360.1191	359.8662	1.378–14
22	2p ⁶ 6s	² S _{1/2}		401.9007	401.5572	2.653–14
23	2p ⁶ 6p	² P _{1/2} ^o		403.3052	402.9603	2.262–14
24	2p ⁶ 6p	² P _{3/2} ^o		406.5339	406.2203	3.266–14
25	2p ⁶ 6d	² D _{3/2}		407.9823	407.6849	1.742–14
26	2p ⁶ 6d	² D _{5/2}		408.7855	408.5064	1.735–14
27	2p ⁶ 6f	² F _{5/2} ^o		409.5470	409.2872	1.310–14
28	2p ⁶ 6f	² F _{7/2} ^o		409.8998	409.6444	1.351–14
29	2p ⁶ 6g	² G _{7/2}		410.0204	409.7698	2.328–14
30	2p ⁶ 6g	² G _{9/2}		410.2293	409.9788	2.357–14

NIST: <http://www.nist.gov/pml/data/asd.cfm>

GRASP: Present results with the GRASP code from 50 configurations and 1235 levels

FAC: Present results with the FAC code from 1592 levels

Table L

Comparison of energies (in Ryd) for the common of levels of W LXV.

Index ^a	Configuration	Level	NIST	GRASP	FAC	MRMP
1	2s ² 2p ⁶	¹ S ₀	0.000	0.0000	0.0000	0.0000
3	2s ² 2p ⁵ 3s	¹ P ₁ ^o	610.640	610.2292	610.1423	610.5354
9	2s ² 2p ⁵ 3p	¹ S ₀	653.859	653.7288	653.5037	653.7409
11	2s ² 2p ⁵ 3d	³ P ₁ ^o	661.507	660.9754	660.7169	661.1325
17	2s ² 2p ⁵ 3d	¹ P ₁ ^o	670.246	670.5722	670.2893	670.6958
19	2s ² 2p ⁵ 3s	³ P ₁ ^o	711.936	711.7088	711.6628	712.0517
21	2s ² 2p ⁵ 3p	³ P ₀	726.088	725.8494	725.6751	725.9370
27	2s2p ⁶ 3p	³ P ₁ ^o	758.302	758.6381	758.2086	758.3025
29	2s ² 2p ⁵ 3d	³ D ₁ ^o	765.027	764.8414	764.5743	764.9308
33	2s2p ⁶ 3p	¹ P ₁ ^o	786.651	787.2457	786.8073	786.8504

^a: See Table 7 for definition of all levelsNIST: <http://www.nist.gov/pml/data/asd.cfm>

GRASP: Present results with the GRASP code from 25 configurations and 157 levels

FAC: Present results with the FAC code from 1147 levels

MRMP: Earlier calculations of Vilkas et al. [27]

Table M

Eigenvectors (EV) for the lowest 33 levels of W LXV from the GRASP code. Numbers outside and inside a bracket correspond to EV and the level, respectively. See Table 7 for the definition of all levels.

Index	Configuration	Level	Eigenvectors
1	$2s^2 2p^6$	1S_0	1.00(1)
2	$2s^2 2p^5 3s$	$^3P_2^o$	1.00(2)
3	$2s^2 2p^5 3s$	$^1P_1^o$	0.34(19)+0.66(3)
4	$2s^2 2p^5 3p$	3P_1	0.09(20)+0.49(4)+0.31(25)+0.10(6)
5	$2s^2 2p^5 3p$	3D_2	0.50(5)+0.17(8)+0.34(24)
6	$2s^2 2p^5 3p$	1P_1	0.08(20)+0.36(25)+0.56(6)
7	$2s^2 2p^5 3p$	3D_3	1.00(7)
8	$2s^2 2p^5 3p$	3P_2	0.67(8)+0.34(24)
9	$2s^2 2p^5 3p$	1S_0	0.37(21)+0.62(9)
10	$2s^2 2p^5 3d$	$^3P_0^o$	1.00(10)
11	$2s^2 2p^5 3d$	$^3P_1^o$	0.32(29)+0.66(11)
12	$2s^2 2p^5 3d$	$^3F_3^o$	0.53(12)+0.07(16)+0.40(31)
13	$2s^2 2p^5 3d$	$^3D_2^o$	0.18(28)+0.55(13)+0.10(30)+0.18(15)
14	$2s^2 2p^5 3d$	$^3F_4^o$	1.00(14)
15	$2s^2 2p^5 3d$	$^1D_2^o$	0.04(28)+0.06(13)+0.41(30)+0.49(15)
16	$2s^2 2p^5 3d$	$^3D_3^o$	0.71(16)+0.27(31)
17	$2s^2 2p^5 3d$	$^1P_1^o$	0.18(29)+0.18(11)+0.62(17)
18	$2s^2 2p^5 3s$	$^3P_0^o$	1.00(18)
19	$2s^2 2p^5 3s$	$^3P_1^o$	0.66(19)+0.34(3)
20	$2s^2 2p^5 3p$	3D_1	0.74(20)+0.23(6)
21	$2s^2 2p^5 3p$	3P_0	0.62(21)+0.37(9)
22	$2s 2p^6 3s$	3S_1	0.08(4)+0.86(22)
23	$2s 2p^6 3s$	1S_0	1.00(23)
24	$2s^2 2p^5 3p$	1D_2	0.49(5)+0.17(8)+0.34(24)
25	$2s^2 2p^5 3p$	3S_1	0.07(20)+0.42(4)+0.26(25)+0.10(6)+0.14(22)
26	$2s 2p^6 3p$	$^3P_0^o$	1.00(26)
27	$2s 2p^6 3p$	$^3P_1^o$	0.66(27)+0.31(33)
28	$2s^2 2p^5 3d$	$^3F_2^o$	0.74(28)+0.20(15)
29	$2s^2 2p^5 3d$	$^3D_1^o$	0.48(29)+0.15(11)+0.35(17)
30	$2s^2 2p^5 3d$	$^3P_2^o$	0.36(13)+0.48(30)+0.14(15)
31	$2s^2 2p^5 3d$	$^1F_3^o$	0.44(12)+0.22(16)+0.34(31)
32	$2s 2p^6 3p$	$^3P_2^o$	1.00(32)
33	$2s 2p^6 3p$	$^1P_1^o$	0.32(27)+0.67(33)

Table N

Eigenvectors (EV) for the lowest 48 levels of W LXVI from the GRASP code. Numbers outside and inside a bracket correspond to EV and the level, respectively. See Table 8 for the definition of all levels.

Index	Configuration	Level	Eigenvectors
1	$2s^2 2p^5$	$2P_{3/2}^o$	1.00(1)
2	$2s^2 2p^5$	$2P_{1/2}^o$	1.00(2)
3	$2s 2p^6$	$2S_{1/2}$	1.00(3)
4	$2s^2 2p^4 3s$	$4P_{5/2}$	0.69(4)+0.31(28)
5	$2s^2 2p^4 3s$	$2P_{3/2}$	0.12(26)+0.56(5)+0.32(29)
6	$2s^2 2p^4 3s$	$2S_{1/2}$	0.23(86)+0.12(27)+0.66(6)
7	$2s^2 2p^4 (^3P)3p$	$4P_{3/2}^o$	0.07(31)+0.31(7)+0.18(92)+0.09(13)+0.16(43)+0.17(33)
8	$2s^2 2p^4 (^3P)3p$	$2D_{5/2}^o$	0.27(38)+0.12(10)+0.29(8)+0.25(32)+0.07(45)
9	$2s^2 2p^4 (^1S)3p$	$2P_{1/2}^o$	0.19(87)+0.04(30)+0.08(40)+0.66(9)
10	$2s^2 2p^4 (^3P)3p$	$4P_{5/2}^o$	0.40(10)+0.27(8)+0.07(32)+0.24(45)
11	$2s^2 2p^4 (^3P)3p$	$2S_{1/2}^o$	0.09(30)+0.18(40)+0.37(11)+0.32(46)
12	$2s^2 2p^4 (^3P)3p$	$4D_{7/2}^o$	0.67(12)+0.32(41)
13	$2s^2 2p^4 (^3P)3p$	$2P_{3/2}^o$	0.24(92)+0.15(39)+0.21(13)+0.13(43)+0.12(33)+0.15(14)
14	$2s^2 2p^4 (^1S)3p$	$2P_{3/2}^o$	0.13(31)+0.12(7)+0.16(13)+0.04(43)+0.50(14)
15	$2s^2 2p^4 (^1D)3d$	$2P_{3/2}$	0.32(50)+0.23(58)+0.07(62)+0.22(55)+0.08(15)
16	$2s^2 2p^4 (^3P)3d$	$4D_{5/2}$	0.13(51)+0.35(16)+0.06(106)+0.10(23)+0.22(54)+0.10(60)
17	$2s^2 2p^4 (^3P)3d$	$4P_{1/2}$	0.12(49)+0.50(17)+0.05(22)+0.22(63)+0.10(53)
18	$2s^2 2p^4 (^3P)3d$	$2F_{7/2}$	0.28(56)+0.06(20)+0.34(18)+0.28(52)
19	$2s^2 2p^4 (^1S)3d$	$2D_{3/2}$	0.17(101)+0.07(58)+0.07(62)+0.62(19)
20	$2s^2 2p^4 (^3P)3d$	$4D_{7/2}$	0.06(56)+0.41(20)+0.22(18)+0.28(61)
21	$2s^2 2p^4 (^3P)3d$	$4F_{9/2}$	0.67(21)+0.32(59)
22	$2s^2 2p^4 (^3P)3d$	$2P_{1/2}$	0.05(49)+0.12(17)+0.50(22)+0.10(63)+0.22(53)
23	$2s^2 2p^4 (^3P)3d$	$2D_{5/2}$	0.05(16)+0.22(106)+0.14(57)+0.26(23)+0.09(54)+0.21(60)
24	$2s^2 2p^4 (^3P)3d$	$2P_{3/2}$	0.18(58)+0.19(62)+0.26(24)+0.10(55)+0.21(15)
25	$2s^2 2p^4 (^1S)3d$	$2D_{5/2}$	0.10(51)+0.11(16)+0.04(57)+0.09(23)+0.61(25)
26	$2s^2 2p^4 3s$	$4P_{3/2}$	0.86(26)+0.12(5)
27	$2s^2 2p^4 3s$	$2P_{1/2}$	0.34(86)+0.67(27)
28	$2s^2 2p^4 3s$	$2D_{5/2}$	0.31(4)+0.67(28)
29	$2s^2 2p^4 3s$	$2D_{3/2}$	0.32(5)+0.66(29)
30	$2s^2 2p^4 (^3P)3p$	$4P_{1/2}^o$	0.27(87)+0.52(30)+0.21(11)
31	$2s^2 2p^4 (^3P)3p$	$4D_{3/2}^o$	0.56(31)+0.14(39)+0.13(13)+0.07(43)+0.07(33)
32	$2s^2 2p^4 (^1D)3p$	$2F_{5/2}^o$	0.12(38)+0.05(10)+0.14(8)+0.53(32)+0.15(45)
33	$2s^2 2p^4 (^1D)3p$	$2P_{3/2}^o$	0.12(7)+0.13(92)+0.18(13)+0.25(43)+0.29(33)
34	$2s 2p^5 (^3P)3s$	$4P_{5/2}^o$	0.96(34)
35	$2s 2p^5 (^3P)3s$	$2P_{3/2}^o$	0.27(89)+0.67(35)
36	$2s 2p^5 (^1P)3s$	$2P_{1/2}^o$	0.05(30)+0.06(11)+0.06(46)+0.10(88)+0.20(90)+0.52(36)
37	$2s 2p^5 (^1P)3s$	$2P_{3/2}^o$	0.04(92)+0.16(89)+0.22(35)+0.52(37)
38	$2s^2 2p^4 (^3P)3p$	$4D_{5/2}^o$	0.55(38)+0.28(10)+0.14(8)
39	$2s^2 2p^4 (^3P)3p$	$2D_{3/2}^o$	0.24(7)+0.16(92)+0.46(39)
40	$2s^2 2p^4 (^3P)3p$	$2P_{1/2}^o$	0.09(87)+0.23(30)+0.23(40)+0.19(11)+0.10(46)+0.10(36)
41	$2s^2 2p^4 (^1D)3p$	$2F_{7/2}^o$	0.32(12)+0.67(41)
42	$2s 2p^5 (^3P)3p$	$4S_{3/2}$	0.11(95)+0.44(130)+0.29(42)+0.13(65)
43	$2s^2 2p^4 (^1D)3p$	$2D_{3/2}^o$	0.16(92)+0.15(13)+0.29(43)+0.27(33)+0.04(89)+0.05(37)
44	$2s 2p^5 (^3P)3p$	$2D_{5/2}$	0.40(133)+0.17(66)+0.44(44)
45	$2s^2 2p^4 (^1D)3p$	$2D_{5/2}^o$	0.14(10)+0.15(8)+0.14(32)+0.52(45)
46	$2s^2 2p^4 (^1D)3p$	$2P_{1/2}^o$	0.07(87)+0.34(40)+0.05(11)+0.52(46)
47	$2s 2p^5 (^1P)3p$	$2P_{1/2}$	0.10(91)+0.18(99)+0.08(70)+0.40(47)+0.22(135)
48	$2s 2p^5 (^1P)3p$	$2D_{3/2}$	0.21(95)+0.05(134)+0.08(65)+0.52(48)+0.10(69)

Table O

Comparison of oscillator strengths (f -values, dimensionless) for some transitions of W LXII. $a \pm b \equiv a \times 10^{\pm b}$.
 See Table 4 for definition of level indices.

I	J	RMBPT	GRASP	R
1	2	3.17-2	3.17-2	9.8-1
1	4	2.07-3	2.07-3	1.0+0
1	6	1.05-1	1.05-1	1.0+0
1	8	4.99-1	4.99-1	1.0+0
1	20	2.07-4	2.07-4	1.3+0
1	22	1.22-4	1.22-4	7.0-1
2	3	3.17-4	3.23-4	1.7+0
3	4	2.48-3	2.48-3	1.0+0
3	5	2.01-2	2.01-2	1.1+0
3	9	1.07-2	1.07-1	1.1+0
3	19	9.34-2	9.34-2	1.0+0
3	20	7.73-2	7.73-2	9.9-1
3	22	2.69-1	2.69-1	1.0+0
5	17	1.27-2	1.65-2	1.0+0
12	22	4.23-3	4.23-3	9.0-1
14	19	1.06-4	1.06-4	1.4+0
19	29	1.38-4	1.38-4	7.7-1
19	31	2.43-4	2.43-4	1.2+0
19	35	5.52-2	5.52-2	1.0+0
19	36	9.69-2	9.69-2	1.1+0
19	37	1.16-2	1.16-2	1.0+0
19	38	6.93-2	6.93-2	1.1+0
19	40	3.91-3	3.91-3	9.1-1
22	27	1.14-4	1.14-4	9.1-1
22	28	1.03-3	1.02-3	1.0+0
22	33	1.01-3	1.01-3	1.3+0
22	35	1.87-3	1.87-3	1.2+0
22	37	1.97-2	1.97-2	1.1+0
22	39	3.71-2	3.71-3	9.9-1
22	40	9.91-3	9.91-3	1.0+0

RMBPT: Earlier results of Safronova and Safronova [23]

GRASP: Present results with the GRASP code from 63 configurations and 2003 levels

R: Ratio of velocity and length forms of f -values

Table P

Comparison of oscillator strengths (f -values, dimensionless) for some transitions of W LXIII. $a \pm b \equiv a \times 10^{\pm b}$.
 See Table 5 for definition of level indices.

I	J	RMBPT	GRASP	R
1	6	5.97-1	6.08-1	1.0+0
2	8	2.76-1	2.81-1	1.0+0
2	9	2.23-1	2.27-1	1.0+0
3	4	3.11-2	3.18-2	1.0+0
3	7	6.43-2	6.45-2	1.0+0
3	8	5.27-2	5.36-2	1.0+0
3	9	3.61-2	3.67-2	1.0+0
3	10	3.12-1	3.19-1	1.0+0
3	12	1.85-2	1.85-2	1.0+0
4	14	4.36-1	4.43-1	1.0+0
5	11	9.10-2	9.27-2	1.1+0
5	17	1.36-1	1.39-1	1.0+0
6	17	2.63-1	2.67-1	1.0+0
6	18	9.49-2	9.66-2	1.0+0
7	16	5.51-2	5.63-2	1.1+0
7	19	1.03-1	1.06-1	1.0+0
7	22	3.45-2	3.44-2	1.1+0
8	15	9.74-2	9.90-2	1.1+0
8	19	8.62-2	8.76-2	1.0+0
8	20	3.39-2	3.45-2	1.0+0
8	21	9.14-2	9.31-2	1.0+0
9	19	1.19-1	1.21-1	1.0+0
9	20	5.15-2	5.24-2	1.0+0
9	21	1.16-1	1.18-1	1.0+0
10	14	2.57-2	2.19-2	1.1+0
10	19	2.20-2	2.20-2	1.0+0
10	22	2.97-1	3.04-1	1.0+0
11	23	1.77-1	1.79-1	1.0+0
11	24	2.50-2	2.53-2	1.0+0
11	25	7.50-2	7.65-2	1.0+0
12	24	1.17-1	1.19-1	1.0+0
12	25	7.35-2	7.47-2	1.0+0
12	26	8.57-2	8.71-2	1.0+0
13	27	1.09-1	1.11-1	1.0+0
14	27	1.05-1	1.78-1	1.0+0
14	28	7.59-2	7.72-2	1.0+0
15	29	6.22-2	6.33-2	1.0+0
15	30	8.59-2	8.73-2	1.0+0
15	32	6.76-2	6.87-2	1.0+0
16	29	6.51-2	6.61-2	1.0+0
16	30	1.87-2	1.90-2	1.0+0
16	31	1.09-1	1.12-1	1.0+0
17	25	1.66-1	1.69-1	1.1+0
18	26	1.98-1	2.02-1	1.1+0
20	32	1.95-1	1.06-1	1.1+0
21	30	3.50-2	6.40-2	1.1+0
21	32	3.31-2	3.35-2	1.1+0
22	31	1.22-1	9.22-2	1.1+0
23	33	3.03-2	3.11-2	1.1+0
24	34	8.49-2	8.64-2	1.1+0
25	33	9.07-2	1.24-1	1.1+0
26	34	3.78-2	5.90-2	1.1+0
26	35	5.39-2	5.39-2	1.1+0

RMBPT: Earlier results of Safronova and Safronova [23]

GRASP: Present results with the GRASP code from 58 configurations and 509 levels

R: Ratio of velocity and length forms of f -values

Table Q

Comparison of radiative rates (A -values, s^{-1}) for some transitions of W LXV. $a \pm b \equiv a \times 10^{\pm b}$.
 See Table 7 for definition of level indices.

I	J	MRMP	GRASP	f (GRASP)	R
1	3	1.206+14	1.5309+14	1.5354-1	1.0-0
1	11	6.551+13	8.2270+13	7.0330-2	9.8-1
1	17	2.613+15	2.8077+15	2.3320+0	9.8-1
1	19	2.694+13	3.8180+13	2.8152-2	9.9-1
1	27	6.243+14	7.7623+14	5.0372-1	1.0-0
1	29	1.227+15	1.3590+15	8.6763-1	9.8-1
1	33	3.350+14	4.4021+14	2.6529-1	1.0-0
1	39	4.193+13	5.3006+13	2.7134-2	9.6-1
1	53	1.021+15	1.0126+15	4.8992-1	9.7-1
1	83	2.365+14	2.3392+14	9.1872-2	9.7-1
1	101	8.690+14	8.9169+14	3.4857-1	9.7-1
1	111	1.118+14	1.3923+14	5.2373-2	9.9-1
1	113	1.850+14	2.2983+14	8.4470-2	9.9-1
1	129	2.953+14	3.0675+14	9.9018-2	9.7-1
1	143	6.038+13	7.5371+13	2.3136-2	9.9-1
1	145	9.992+13	1.2558+14	3.8142-2	9.8-1
2	4	2.917+10	3.0224+10	1.8434-2	9.2-1
2	6	2.395+11	2.4114+11	1.1881-2	9.8-1
2	7	1.669+12	1.6814+12	1.9361-1	1.1-0
2	8	9.092+11	9.1611+11	7.1771-2	9.7-1
2	22	1.580+13	1.5536+13	6.1622-2	9.5-1
2	40	4.805+13	5.4832+13	6.6094-2	1.0-0
2	41	2.845+13	3.2448+13	6.5169-2	1.0-0
2	42	3.484+13	4.0782+13	1.0485-1	9.9-1
2	68	2.616+13	2.9775+13	1.7587-2	1.0-0
2	71	2.101+13	2.4627+13	3.2866-2	9.8-1
3	6	1.342+12	1.3518+12	1.1467-1	1.0-0
3	8	8.614+11	8.6757+11	1.1693-1	1.0-0
3	9	2.411+12	2.4572+12	5.3889-2	9.5-1
3	23	2.171+13	2.1941+13	4.6553-2	9.5-1
3	41	2.894+13	3.2979+13	1.1095-1	9.9-1
3	43	2.956+13	3.4575+13	6.3790-2	9.9-1
3	45	3.309+13	3.8940+13	2.3629-2	1.0-0
3	73	2.062+13	2.4239+13	7.6916-3	1.0-0

MRMP: Earlier results of Vilkas et al. [27]

GRASP: Present results with the GRASP code from 25 configurations and 157 levels

R: Ratio of velocity and length forms of f -values

Explanation of Tables

Table 1. Energies (Ryd) for the lowest 220 levels of W LIX and their lifetimes (τ , s).

Index	Level Index
Configuration	The configuration to which the level belongs
Level	The <i>LSJ</i> designation of the level
GRASP	Present energies from the GRASP code with 12 652 level calculations
FAC	Present energies from the FAC code with 38 694 level calculations
τ (s)	Lifetime of the level in s

Table 2. Energies (Ryd) for the lowest 220 levels of W LX and their lifetimes (τ , s).

Index	Level Index
Configuration	The configuration to which the level belongs
Level	The <i>LSJ</i> designation of the level
GRASP	Present energies from the GRASP code with 3533 level calculations
FAC	Present energies from the FAC code with 14 608 level calculations
τ (s)	Lifetime of the level in s

Table 3. Energies (Ryd) for the lowest 215 levels of W LXI and their lifetimes (τ , s).

Index	Level Index
Configuration	The configuration to which the level belongs
Level	The <i>LSJ</i> designation of the level
GRASP	Present energies from the GRASP code with 4364 level calculations
FAC	Present energies from the FAC code with 27 122 level calculations
τ (s)	Lifetime of the level in s

Table 4. Energies (Ryd) for the lowest 148 levels of W LXII and their lifetimes (τ , s).

Index	Level Index
Configuration	The configuration to which the level belongs
Level	The <i>LSJ</i> designation of the level
GRASP	Present energies from the GRASP code with 2003 level calculations
FAC	Present energies from the FAC code with 12 139 level calculations
τ (s)	Lifetime of the level in s

Table 5. Energies (Ryd) for the lowest 210 levels of W LXIII and their lifetimes (τ , s).

Index	Level Index
Configuration	The configuration to which the level belongs
Level	The <i>LSJ</i> designation of the level
GRASP	Present energies from the GRASP code with 509 level calculations
FAC	Present energies from the FAC code with 991 level calculations
τ (s)	Lifetime of the level in s

Table 6. Energies (Ryd) for the $2p^5n\ell$ ($n \leq 20$) levels of W LXIV.

Index	Level Index
Configuration	The configuration to which the level belongs
Level	The <i>LSJ</i> designation of the level
FAC	Present energies from the FAC code with 1592 level calculations

Table 7. Energies (Ryd) for the lowest 121 levels of W LXV and their lifetimes (τ , s).

Index	Level Index
Configuration	The configuration to which the level belongs
Level	The <i>LSJ</i> designation of the level
GRASP	Present energies from the GRASP code with 157 level calculations
FAC	Present energies from the FAC code with 1147 level calculations
MRMP	Earlier energies of Vilas et al. [27]
τ (GRASP, s)	Lifetime of the level in s from the GRASP calculations
τ (MRMP, s)	Lifetime of the level in s from the Vilkas et al. [27]

Table 8. Energies (Ryd) for the lowest 150 levels of W LXVI and their lifetimes (τ , s).

Index	Level Index
Configuration	The configuration to which the level belongs
Level	The <i>LSJ</i> designation of the level
GRASP	Present energies from the GRASP code with 501 level calculations
FAC	Present energies from the FAC code with 1113 level calculations
τ (s)	Lifetime of the level in s

Table 9. Transition wavelengths (λ_{ij} in Å), radiative rates (A_{ji} in s^{-1}), oscillator strengths (f_{ij} , dimensionless), and line strengths (S , in atomic units) for electric dipole (E1), and A_{ji} for electric quadrupole (E2), magnetic dipole (M1), and magnetic quadrupole (M2) transitions of W LIX. The ratio R(E1) of velocity and length forms of A -values for E1 transitions is listed in the last column.

i and j	The lower (i) and upper (j) levels of a transition as defined in Table 1.
λ_{ij}	Transition wavelength (in Å)
A_{ji}^{E1}	Radiative transition probability (in s^{-1}) for the E1 transitions
f_{ij}^{E1}	Absorption oscillator strength (dimensionless) for the E1 transitions
S^{E1}	Line strength in atomic unit (a.u.), 1 a.u. = 6.460×10^{-36} cm ² esu ² for the E1 transitions
A_{ji}^{E2}	Radiative transition probability (in s^{-1}) for the E2 transitions
A_{ji}^{M1}	Radiative transition probability (in s^{-1}) for the M1 transitions
A_{ji}^{M2}	Radiative transition probability (in s^{-1}) for the M2 transitions
R(E1)	Ratio of velocity and length forms of A - (or f - and S -) values for the E1 transitions
$a \pm b$	$\equiv a \times 10^{\pm b}$

Table 10. Transition wavelengths (λ_{ij} in Å), radiative rates (A_{ji} in s^{-1}), oscillator strengths (f_{ij} , dimensionless), and line strengths (S , in atomic units) for electric dipole (E1), and A_{ji} for electric quadrupole (E2), magnetic dipole (M1), and magnetic quadrupole (M2) transitions of W LX. The ratio R(E1) of velocity and length forms of A -values for E1 transitions is listed in the last column.

i and j	The lower (i) and upper (j) levels of a transition as defined in Table 2.
λ_{ij}	Transition wavelength (in Å)
A_{ji}^{E1}	Radiative transition probability (in s^{-1}) for the E1 transitions
f_{ij}^{E1}	Absorption oscillator strength (dimensionless) for the E1 transitions
S^{E1}	Line strength in atomic unit (a.u.), 1 a.u. = 6.460×10^{-36} cm ² esu ² for the E1 transitions
A_{ji}^{E2}	Radiative transition probability (in s^{-1}) for the E2 transitions
A_{ji}^{M1}	Radiative transition probability (in s^{-1}) for the M1 transitions
A_{ji}^{M2}	Radiative transition probability (in s^{-1}) for the M2 transitions
R(E1)	Ratio of velocity and length forms of A - (or f - and S -) values for the E1 transitions
$a \pm b$	$\equiv a \times 10^{\pm b}$

Table 11. Transition wavelengths (λ_{ij} in Å), radiative rates (A_{ji} in s^{-1}), oscillator strengths (f_{ij} , dimensionless), and line strengths (S , in atomic units) for electric dipole (E1), and A_{ji} for electric quadrupole (E2), magnetic dipole (M1), and magnetic quadrupole (M2) transitions of W LXI. The ratio R(E1) of velocity and length forms of A -values for E1 transitions is listed in the last column.

i and j	The lower (i) and upper (j) levels of a transition as defined in Table 3.
λ_{ij}	Transition wavelength (in Å)
A_{ji}^{E1}	Radiative transition probability (in s^{-1}) for the E1 transitions
f_{ij}^{E1}	Absorption oscillator strength (dimensionless) for the E1 transitions
S^{E1}	Line strength in atomic unit (a.u.), 1 a.u. = 6.460×10^{-36} cm ² esu ² for the E1 transitions
A_{ji}^{E2}	Radiative transition probability (in s^{-1}) for the E2 transitions
A_{ji}^{M1}	Radiative transition probability (in s^{-1}) for the M1 transitions
A_{ji}^{M2}	Radiative transition probability (in s^{-1}) for the M2 transitions
R(E1)	Ratio of velocity and length forms of A - (or f - and S -) values for the E1 transitions
$a \pm b$	$\equiv a \times 10^{\pm b}$

Table 12. Transition wavelengths (λ_{ij} in Å), radiative rates (A_{ji} in s^{-1}), oscillator strengths (f_{ij} , dimensionless), and line strengths (S , in atomic units) for electric dipole (E1), and A_{ji} for electric quadrupole (E2), magnetic dipole (M1), and magnetic quadrupole (M2) transitions of W LXII. The ratio R(E1) of velocity and length forms of A -values for E1 transitions is listed in the last column.

i and j	The lower (i) and upper (j) levels of a transition as defined in Table 4.
λ_{ij}	Transition wavelength (in Å)
A_{ji}^{E1}	Radiative transition probability (in s^{-1}) for the E1 transitions
f_{ij}^{E1}	Absorption oscillator strength (dimensionless) for the E1 transitions
S^{E1}	Line strength in atomic unit (a.u.), 1 a.u. = 6.460×10^{-36} cm ² esu ² for the E1 transitions
A_{ji}^{E2}	Radiative transition probability (in s^{-1}) for the E2 transitions
A_{ji}^{M1}	Radiative transition probability (in s^{-1}) for the M1 transitions
A_{ji}^{M2}	Radiative transition probability (in s^{-1}) for the M2 transitions
R(E1)	Ratio of velocity and length forms of A - (or f - and S -) values for the E1 transitions
$a \pm b$	$\equiv a \times 10^{\pm b}$

Table 13. Transition wavelengths (λ_{ij} in Å), radiative rates (A_{ji} in s^{-1}), oscillator strengths (f_{ij} , dimensionless), and line strengths (S , in atomic units) for electric dipole (E1), and A_{ji} for electric quadrupole (E2), magnetic dipole (M1), and magnetic quadrupole (M2) transitions of W LXIII. The ratio R(E1) of velocity and length forms of A -values for E1 transitions is listed in the last column.

i and j	The lower (i) and upper (j) levels of a transition as defined in Table 5.
λ_{ij}	Transition wavelength (in Å)
A_{ji}^{E1}	Radiative transition probability (in s^{-1}) for the E1 transitions
f_{ij}^{E1}	Absorption oscillator strength (dimensionless) for the E1 transitions
S^{E1}	Line strength in atomic unit (a.u.), 1 a.u. = 6.460×10^{-36} cm ² esu ² for the E1 transitions
A_{ji}^{E2}	Radiative transition probability (in s^{-1}) for the E2 transitions
A_{ji}^{M1}	Radiative transition probability (in s^{-1}) for the M1 transitions
A_{ji}^{M2}	Radiative transition probability (in s^{-1}) for the M2 transitions
R(E1)	Ratio of velocity and length forms of A - (or f - and S -) values for the E1 transitions
$a \pm b$	$\equiv a \times 10^{\pm b}$

Table 14. Transition wavelengths (λ_{ij} in Å), radiative rates (A_{ji} in s^{-1}), oscillator strengths (f_{ij} , dimensionless), and line strengths (S , in atomic units) for electric dipole (E1), and A_{ji} for electric quadrupole (E2), magnetic dipole (M1), and magnetic quadrupole (M2) transitions of W LXIV. The ratio R(E1) of velocity and length forms of A -values for E1 transitions is listed in the last column.

i and j	The lower (i) and upper (j) levels of a transition as defined in Table 6.
λ_{ij}	Transition wavelength (in Å)
A_{ji}^{E1}	Radiative transition probability (in s^{-1}) for the E1 transitions
f_{ij}^{E1}	Absorption oscillator strength (dimensionless) for the E1 transitions
S^{E1}	Line strength in atomic unit (a.u.), 1 a.u. = 6.460×10^{-36} cm ² esu ² for the E1 transitions
A_{ji}^{E2}	Radiative transition probability (in s^{-1}) for the E2 transitions
A_{ji}^{M1}	Radiative transition probability (in s^{-1}) for the M1 transitions
A_{ji}^{M2}	Radiative transition probability (in s^{-1}) for the M2 transitions
R(E1)	Ratio of velocity and length forms of A - (or f - and S -) values for the E1 transitions
$a \pm b$	$\equiv a \times 10^{\pm b}$

Table 15. Transition wavelengths (λ_{ij} in Å), radiative rates (A_{ji} in s^{-1}), oscillator strengths (f_{ij} , dimensionless), and line strengths (S , in atomic units) for electric dipole (E1), and A_{ji} for electric quadrupole (E2), magnetic dipole (M1), and magnetic quadrupole (M2) transitions of W LXV. The ratio R(E1) of velocity and length forms of A -values for E1 transitions is listed in the last column.

i and j	The lower (i) and upper (j) levels of a transition as defined in Table 7.
λ_{ij}	Transition wavelength (in Å)
A_{ji}^{E1}	Radiative transition probability (in s^{-1}) for the E1 transitions
f_{ij}^{E1}	Absorption oscillator strength (dimensionless) for the E1 transitions
S^{E1}	Line strength in atomic unit (a.u.), 1 a.u. = 6.460×10^{-36} cm ² esu ² for the E1 transitions
A_{ji}^{E2}	Radiative transition probability (in s^{-1}) for the E2 transitions
A_{ji}^{M1}	Radiative transition probability (in s^{-1}) for the M1 transitions
A_{ji}^{M2}	Radiative transition probability (in s^{-1}) for the M2 transitions
R(E1)	Ratio of velocity and length forms of A - (or f - and S -) values for the E1 transitions
$a \pm b$	$\equiv a \times 10^{\pm b}$

Table 16. Transition wavelengths (λ_{ij} in Å), radiative rates (A_{ji} in s^{-1}), oscillator strengths (f_{ij} , dimensionless), and line strengths (S , in atomic units) for electric dipole (E1), and A_{ji} for electric quadrupole (E2), magnetic dipole (M1), and magnetic quadrupole (M2) transitions of W LXVI. The ratio R(E1) of velocity and length forms of A -values for E1 transitions is listed in the last column.

i and j	The lower (i) and upper (j) levels of a transition as defined in Table 8.
λ_{ij}	Transition wavelength (in Å)
A_{ji}^{E1}	Radiative transition probability (in s^{-1}) for the E1 transitions
f_{ij}^{E1}	Absorption oscillator strength (dimensionless) for the E1 transitions
S^{E1}	Line strength in atomic unit (a.u.), 1 a.u. = 6.460×10^{-36} cm ² esu ² for the E1 transitions
A_{ji}^{E2}	Radiative transition probability (in s^{-1}) for the E2 transitions
A_{ji}^{M1}	Radiative transition probability (in s^{-1}) for the M1 transitions
A_{ji}^{M2}	Radiative transition probability (in s^{-1}) for the M2 transitions
R(E1)	Ratio of velocity and length forms of A - (or f - and S -) values for the E1 transitions
$a \pm b$	$\equiv a \times 10^{\pm b}$